London

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OXFORD UNIVERSITY PRESS WAREHOUSE

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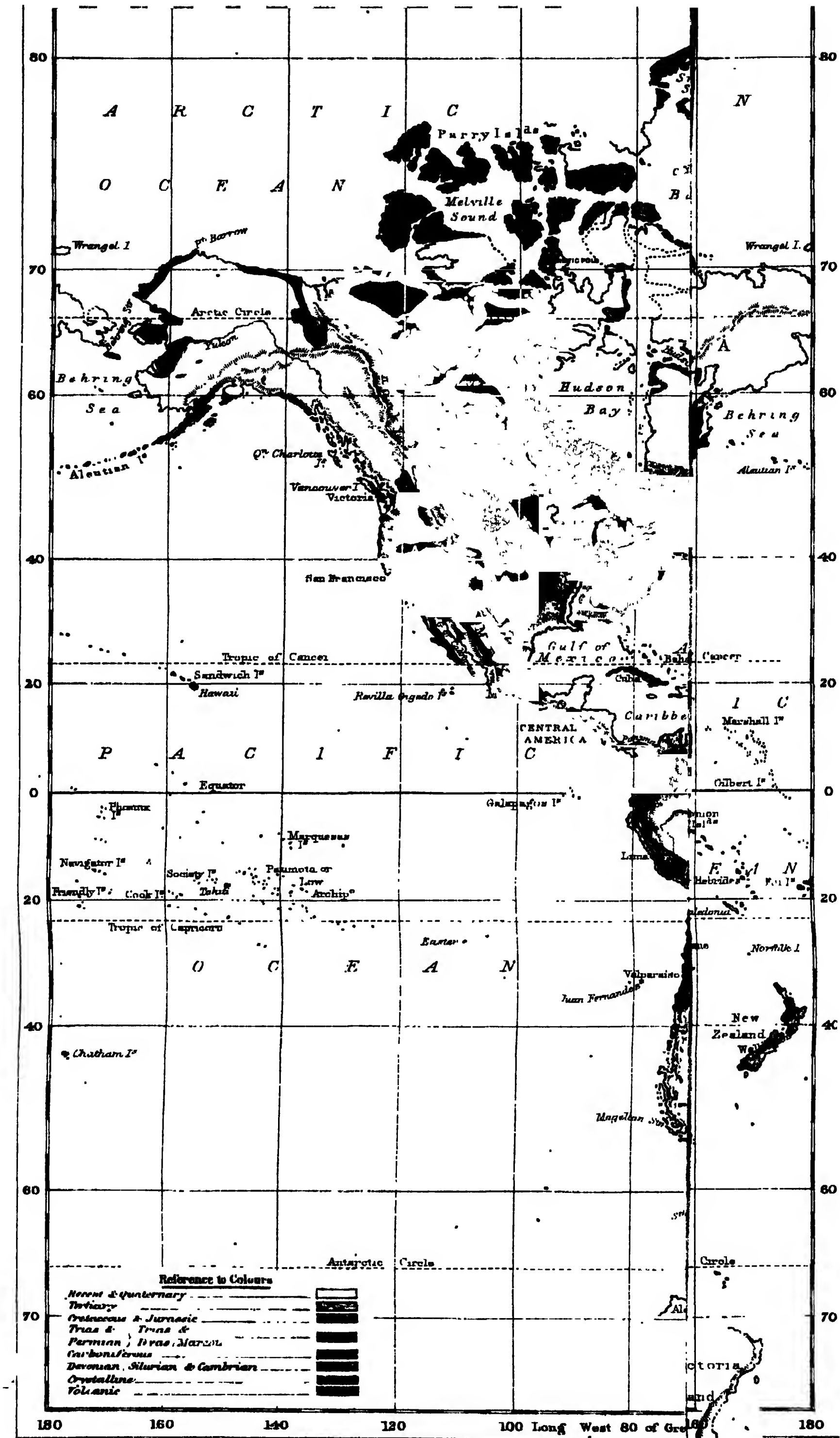

A R C T I C
O C E A N
Parry Is
Melville Sound
Wrangel I
Pt. Barrow
Arctic Circle
Yukon
Behring Sea
Hudson Bay
Aleutian Is
Qn. Charlotte Is
Vancouver I.
Victoria
San Francisco
Gulf of Mexico
Tropic of Cancer
Sandwich Is
Hawaii
Revilla Gigedo Is
Cuba
Caribbe
CENTRAL AMERICA
P A C I F I C
Equator
Galapagos Is
Marshall Is
Gilbert Is
Phœnix I.
Marquesas Is
Navigator Is
Society Is
Paumota or Low Archip.
Friendly Is
Cook Is
Tahiti
Tropic of Capricorn
O C E A N
Easter
Valparaiso
Juan Fernandez
Norfolk I.
Lima
Hebrides
Fiji Is
New Zealand
Chatham Is
Magellan St.
Antarctic Circle
Reference to Colours
Recent & Quaternary
Tertiary
Cretaceous & Jurassic
Trias & Permian
Carboniferous
Devonian, Silurian & Cambrian
Crystalline
Volcanic
100 Long. West 80 of Gr

GEOLOGY

CHEMICAL, PHYSICAL, AND STRATIGRAPHICAL,.

BY

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IN TWO VOLUMES

VOL. I

CHEMICAL AND PHYSICAL

Oxford

AT THE CLARENDON PRESS

MDCCCLXXXVI 1876

PRELIMINARY REMARKS.

SO many excellent elementary works on Geology have been published during the last few years, that any new work on the subject might be thought unnecessary. In a science like Geology, however, where facts have to be recorded and hypotheses put forward, although text-books must record the same facts and describe the same phenomena, the interpretation of them is, in many cases, open to such different constructions (each necessarily bearing the stamp of the author's own particular views), that, with a common framework, there may be great diversity of treatment and of opinion on the theoretical questions involved. For example, the fundamental question of *time and force* has given rise to two schools, one of which adopts uniformity of action in all time,—while the other considers that the physical forces were more active and energetic in geological periods than at present.

On the Continent and in America the latter view prevails, but in this country the theory of uniformity has been more generally held and taught. To this theory I have always seen very grave objections; so when asked by the Delegates of the Press, soon after my appointment here in 1874, to undertake a work of this description, however much I might have hesitated under other circumstances, I felt I should be supplying a want by placing before the student the views of a school which, until of late, has hardly had its exponent in English text-books.

The eloquence and ability with which Uniformitarianism has been advocated, furthered by the palpable objections to the extreme views held by some eminent geologists of the other school, led in England to its very wide acceptance. But it must be borne in mind that uniformitarian doctrines have probably been carried further by his followers than by their distinguished advocate, Sir Charles Lyell, and also that the doctrine of Non-uniformity must not be confounded with a blind reliance on catastrophes; nor does it, as might be supposed from the tone of some of its opponents, involve any questions respecting uniformity of law, but only those respecting uniformity of action.

I myself have long been led to conclude that the phenomena of

Geology, so far from showing uniformity of action in all time, present an unceasing series of changes dependent upon the circumstances of the time; and that, while the laws of Chemistry and Physics are unchangeable and as permanent as the material universe itself, the exhibition of the consequences of those laws in their operation on the earth has been, as new conditions and new combinations successively arose in the course of its long geological history, one of constant variation in degree and intensity of action.

The first object, however, of the student, of whatever school, should be to study the laws to which the materials and masses he has to deal with are subject, and then to consider what may have been their action under varying conditions in past time. With this object in view I have divided the work into four parts: the first treating of the composition of minerals and rocks forming the crust of the earth; the second,—the mode of action of geological agencies under existing and under past conditions; while the third and fourth will treat of the succession of the groups of sedimentary strata and of the life thereof, and of some of the theoretical questions connected with the physical conditions prevailing during former periods of the earth's history.

The first chapters are intended to give the reader a general sketch of the nature and distribution of the materials with which the Geologist has most commonly to deal, and are therefore arranged to meet this need rather than with a view to technical classification. The student must fill up these outlines by reference to special works on Chemistry, Mineralogy, and Petrology; the same with the chapter on Palæontology and Biology: these subjects require separate and patient study.

After tracing the combination of the elementary substances that enter into the composition of the minerals forming the rocks of which the crust of the earth consists, and the character of these rocks, I have described in Chapter IV the processes of change by which the older of these rocks have, in consequence of alteration and decomposition, furnished the materials for the newer rocks, and shown the process of evolution, as it were, by which the stratified have been developed from the unstratified rocks. In this remodelling of the original materials, there has been incessant change from the more complex to the more simple forms, and the stratified rocks represent, so to speak, the insoluble residue of the primeval and unstratified rocks set free by their decomposition and the removal by the surface waters of their soluble bases into the common receptacle—the great ocean,—subject always of course to the reactions which have there modified the character of those salts. The residue thus eliminated after the destruction of the multiple compounds they formed in their first stages consists of a very limited number of substances, and those being comparatively indestructible, have passed through successive stratigraphical

reconstructions, with no further change than that of wear and diminution in size.

The observations on the deep-sea deposits made on the 'Challenger' and various foreign expeditions, and those of M. Delesse on coast lines, recorded in Chapter VIII, supply data of material importance in questions of Stratigraphical Geology.

In a succeeding chapter I have treated the subject of Hydro-geology more fully than usual on account of the importance of a clear understanding of the laws which regulate the underground circulation of waters in relation to the many chemical and physical questions connected with metamorphism, mineral veins, and volcanic phenomena, and its practical value.

In the chapter on Volcanoes I have enlarged on the views I brought before the York Meeting of the British Association in 1882, showing that more importance attaches to the surface and underground waters within a given depth than to water supposed to be present in the volcanic foci.

I have also dwelt at some length on the age and theory of Mountain-chains and on Mineral Veins, as they are subjects which have not generally been treated at any length.

It may seem that I have given too much space to the minor forces which have affected the crust of the earth; but I believe that it is not possible for the student to reason on the major disturbances, such, for example, as the great problems of the elevation of Mountain-chains and of Continents, or of Metamorphism, etc., without an intimate knowledge of all the elements,—such as the complex structure of Faults, the chemistry of Mineral Veins, and the wide net-work of Joints,—that may either have influenced the results, or have been conjoint products of the same causes. For similar reasons the study of Earthquake shocks and movements, and of Ice and Ice-motion, in reference to the rending, erosion and sculpturing of the surface, is of great importance.

On the other hand, the very important subject of Petrology, both macro- and microscopic, which is more fully treated of in text-books, I have touched upon slightly and chiefly from the chemical side of the question. It is in fact a subject that would now require a volume by itself. Its present aims and objects, together with some of the results at which Petrologists have arrived, and of the difficulties (and they are not few) which yet remain for solution, will be found very ably stated in the recent Anniversary address (February 1885) of Professor Bonney to the Geological Society of London.

In conclusion, it has been my aim to furnish both the student and the general reader with that elementary knowledge of the several branches of our science which may best enable him to pursue his studies for a time independent of other aid; or should he wish to proceed further, it will prepare him to read with advantage the special works indispensable to the

more advanced student. The first chapters are therefore intended for those who approach the subject for the first time; while the parts printed in small type can be passed over by others and by the general reader.

At the same time I have not been unmindful of what is required for the advanced student, and for this purpose I have treated some physical and chemical problems in such a manner that he may see not only the actual progress that has been made, but also the difficulties with which many of them are still surrounded, and the direction to be taken for their further investigation. To assist such inquiry, I have referred to some of the principal original papers on the several subjects; and the field once entered, the advanced student will have no difficulty in enlarging his range of inquiry. I have adopted this course because it is desirable that he should have put before him the different phases of the many questions in Geology which are still '*sub judice*,' both as a training as to what to observe and how to balance evidence, and as an inducement to independent research.

This mode of treatment has led me beyond the bounds I originally contemplated, and to the necessity of the work being in two volumes instead of one. Although I feel that there are many objections to the publication of a work in separate parts, yet, besides the wish to avoid further delay, the subjects treated in the two volumes are distinct, the chapters of this first volume consisting of studies preliminary to any general work on Structural and Palæontological Geology, and to a certain extent as introductory to Physical Geography.

The second volume will treat, firstly, of Stratigraphical and Palæontological Geology, and of the Succession of Life on the earth; and secondly, of those theoretical questions connected with cosmical and physical phenomena which relate to the Evolution of the Globe and Historical Geology.

The frontispiece map of the World is a reduction from the large map constructed by Professor Jules Marcou, to whom I am indebted for its revision; and I only regret that the small size of the reduction renders it impossible to do justice to the larger work. I have also availed myself of the observations made during the recent British and American voyages to the higher latitudes of Smith's Sound,—of the Swedish and Norwegian expeditions along the polar Asiatic lands,—and of the Austrian expedition to Franz-Joseph's Land, for additional information respecting the geology of those inaccessible regions.

Notwithstanding its small size, Messrs. W. and A. Keith Johnston have very successfully given the main features of this map; so also in the maps of Coral Islands and Volcanoes, where I have to acknowledge their assistance in many of the details.

To the Council of the Geological Society of London, and to the authors of several papers in the Quarterly Journal of that Society, I have

to express my thanks for the use of woodcuts. For many illustrations of Volcanic phenomena by the late Mr. Poulett Scrope, and for other original sketches, my thanks are due to Professor Judd. In the chapters on Coral Islands, I have largely availed myself of the illustrations given by Darwin and Dana in their respective works on the subject; on glacial phenomena in Smith's Sound, to Kane's 'Voyages'; on ancient volcanic phenomena, to the several papers on that subject by Dr. Archibald Geikie and Professor Judd; on Mineral Veins, to the works of Cotta and Whitney; and on Mountain-sections to the works of A. Favre, Escher von der Linth, and Heim. To my colleague Professor Moseley I am indebted for various friendly suggestions in the biological chapter.

I have likewise largely made use of the publications of the Geological Survey, especially the Horizontal Sections, to illustrate various geological features, as it is a matter of importance to the student that a section should be drawn, so far as possible, in its exact relative proportions, and on a true scale of depth and distance. I have therefore taken, wherever practicable, in illustration of the superposition and dimensions of the strata and of the throw of faults, the Survey's Sections, which are made to a true scale of six inches to the mile, both for distance and depth. When the size of the page has not allowed of the introduction of a section on this scale, the figure is reduced, but the proportions are kept, and the fractional size given. There is the further advantage in having illustrations which explain some actual and known ground.

By the kind permission of the Radcliffe Librarian, Sir Henry W. Acland, I have had the opportunity of having reduced sketches made from drawings in the University Museum, many of which belonged originally to our eminent geologist, Dr. Buckland.

In passing the proofs through the press I have had the advantage of the assistance and criticisms of Professor T. Rupert Jones.

This volume has been so long in hand, that many valuable publications which I should have been glad to profit by have appeared since much of it was in print. I have been able to refer to a few in notes, but I have to regret the omission of others.

JOSEPH PRESTWICH.

OXFORD,
October, 1885.

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ERRATA.

Page 9, fourth column, *for* Zircoma *read* Zirconia.
,, 30, eleven lines from bottom, *for* Nummulitic *read* Eocene.
,, 37, fifteen lines from top, *after* Loc. *add* The Andes.
,, 40, eight lines from bottom, *to* Loc. (of diorite) *add* The Pyrenees.
,, 57, seven lines from top, *for* 14 *read* 15.
,, 66, eleven lines from top, *after* 1. *insert* Spongiaria; *and dele* Spongidæ.
,, 67, eleven lines from top, *for* Astrea *read* Astræa.
,, 68, thirty-two lines from top, *for* Leperditoidæ *read* Leperditiadæ.
,, 70, fourteen lines from top, *dele* Myriaporidæ.
,, 72, first line, *for* ordinary Mollusca *read* Molluscoidea and Mollusca.
,, 87, nineteen lines from top, *for* 8,000 *read* 20.000.
,, 101, note, *for* Kingsdown *read* Kingsgate.
,, 114, five lines from bottom, Fig. 37, *transpose* 'lower' and 'upper.'
,, 123, seventeen lines from top, *for* 50 to 80 *read* 44 to 81.
,, 137, six lines from bottom, *for* 60° F. to 120° F. *read* −60° F. to −120° F.
,, 142, thirteen lines from bottom, *after* deep *insert* *b*.
,, 142, seventeen lines from bottom, *for* *b* read *w*.
,, 159, twenty-three lines from top, *dele* [1]; note [2] applies both to the experiments on 'soil' and 'chalk'; *transpose* note [1] to p. 157, *after* 'foot' line eighteen.
,, 203, five lines from top, *for* strong *read* stony.
,, 266, twenty-nine lines from top, *for* dip *read* strike.
,, 271, title of Fig. 143, *for* fointed *read* jointed.
,, 296, twenty-six and thirty-one lines from top, *for* Ross-shire *read* Sutherland.
,, 338, eight lines from top, *for* modular read nodular.
,, 349, nineteen lines from top, 'fine crystals' refer to the Specular Iron.
,, 351, twenty-four lines from top, *for* sulphides *read* ores.
,, 355, three lines from top, *for* '*c*, *b*,' *read* '*b*, *c*.'
,, 434, fourteen lines from top, *for* they *read* these.
,, 437, twenty-seven lines from top, *dele* only.
,, 439, thirteen lines from top, *for* be *read* have been.
,, 440, six lines from top, *for* scated *read* schistose.

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PART I.

CHAPTER I.

OBJECTS AND METHODS OF GEOLOGY.

GEOLOGY AS A SCIENCE. ITS DEFINITION AND SCOPE. INTERPRETATION OF THE PHENOMENA. BEARING OF MODERN CAUSES. METHODS OF INVESTIGATION. FROM THE GENERAL TO THE SPECIAL. OTHER SCIENCES IN RELATION TO GEOLOGY. GEOLOGICAL EQUIPMENT AND METHODS OF OBSERVING AND COLLECTING.

Geology, as a science, had no existence previously to the close of the last century. A few classical and mediæval authors indulged in speculations about the Earth, which no doubt occasionally approached the truth; but such speculations, being made on isolated facts, in ignorance of their special bearing and of the cognate phenomena, usually passed into mere fable.

Thus, the great volcanic eruptions of Vesuvius and Etna could not fail to attract attention, and to provoke discussion as to their origin, which by some classical writers was justly attributed to subterranean heat, or 'central fires;' but the same fires were connected with the origin of all things and of life. Again, in early times, the presence of marine shells far inland, and on hills above the sea-level, gave rise, rightly, to the idea that the sea had been where continents now are; but no successful attempt was made to go beyond this elementary stage; while subsequently, in the Middle Ages, all such fossils were more generally referred to one universal deluge, or were looked on as imitative forms, due to a certain plastic and supposed modelling power in the earth[1].

Towards the end of last century the structure of the rock-masses of the globe began to be more systematically studied and better understood. Werner, Hutton, Dolomieu, Saussure, and others showed that the earth consisted partly of sedimentary stratified rocks, and partly of unstratified rocks. But little was understood of the order of succession of life on the earth, until, in 1799, the researches of William Smith proved, not only that the various strata held a definite and uniform relation one to the other, but also that each group has its own distinctive set of organic remains

[1] For much curious information on this subject, see the first three chapters of Lyell's 'Principles of Geology,' D'Archiac's 'Histoire des Progrès de la Géologie,' vol. i., and Bertrand's 'Révolutions du Globe,' pp. 1–30.

—that, in fact, each successive period of the globe was characterised by different forms of life, both vegetable and animal.

Geology, as it is now understood, is that science which deals with the structure, and with the history of the Earth, and of the life upon it in all past times. It commences with questions of cosmogony, and ends in the 'status quo' of the present period. It is divided into two parts; one dealing with inorganic matter and the laws to which such matter is subject; and the other with life and all its successive developments on the globe. These form two great divisions—

1st. Physical and Stratigraphical Geology.

2nd. Palæontological Geology.

The former involves the study of all those changes, whether physical or chemical, through which the crust of the earth has passed, and deals with the great questions connected with the effects of heat, energy, and force, exhibited in the action of the igneous rocks and disturbance of the sedimentary strata. Under the first heading we have also to consider the origin and mode of formation of the sedimentary strata. This constitutes one primary object of geological research. The other division deals with the successional development of life during the several geological periods, investigates its character, and studies the relation of every organic form in space and in time. This can only be done by proceeding from the known to the unknown,—by the study of existing nature, and seeing how far the phenomena of the past agree with those of the present time, and how far the latter will serve to explain the former. On one part of this question geologists differ. They all agree in the leading facts of geology, such as the order of superposition of the strata, the great age of the earth, the nature and character of the organic remains or fossils characterising successive formations, but they differ in their interpretation of the manner in which the successive changes have been brought about, and on the equality of the forces in action in past and present periods of the earth's history.

No one now would deny the identity of natural agencies in all time, or would call in unknown forces to explain that which we yet fail to understand. One school, however, considers that the causes at present in action on the surface of the globe are not only those which have ever been in action, but also maintain that at all former periods they have been *equal in kind and in degree*, and that the energy with which the forces of nature now operate are sufficient, *with unlimited time*, to account for all past phenomena. The other school, on the contrary, considers that, while identical in kind, the causes in operation in past times were affected by a more active and energetic action of those forces than obtains at present.

The further discussion of this question must be reserved until the reader is master of the facts of the science. In the meantime he should

study the chapters on the Causes at present in action and on Stratigraphical Geology. A wider course of reading is, however, needed for the advanced student. The founders of the Burdett-Coutts Scholarship wisely determined that the examination of the candidates was not to be restricted to Geology, but that their studies should embrace Biology and Chemistry. The subjects might with advantage be extended to certain branches of Physics, such as Heat and Thermodynamics, Hydrostatics, and Mechanics. The future progress of Geology depends much on specialised researches in these several collateral sciences.

But the fundamental and indispensable qualification for the geological student is accurate and true observation in the field, the habit of careful record of facts on the spot, and the power of discerning the bearing of all the various phenomena that come before him, and apportioning their relative value. Without this the abstract sciences are of no avail; and the student will often find himself launched in a wrong direction, and in fruitless inquiries. The real class-rooms of a geologist are to be found in quarries, pits, railway sections, cliffs, mountain-passes, and ravines. To these the student must resort to obtain that mastery of the science which will enable him to interpret facts rightly and to draw conclusions justly. It is this direct study of nature, this exploration of ground ever new, this contact with scenery ever varied, this constant exercise of the powers of observation, with the seeing and handling of the forms of life long passed away, that give real geological knowledge and power. It is the acquisition of the positive facts, and the ever novel subjects of thought and reflection which the varied phenomena present, that constitute so great a charm and pleasure to those engrossed in special research, or to those who are merely in search of healthful change, new scenes and ideas, and recreation.

The geologist requires but little with him to take the field. A good walking-dress, with an extra number of pockets, is convenient. A map and note-book are necessary; and he should be provided with a hammer and chisel suited to the character of the rocks he may have to deal with, as well as a large knife for clays and such like soft strata. He should also have a pocket-lens of low power, and a Codington or some other high-power lens, a clinometer for measuring the angle of dip, a compass[1], and a tape or other measure of not less than six feet long—one of twenty feet is better. It may often be convenient to be provided with an aneroid barometer, a small bar-magnet, and also a wire sieve. For

[1] In taking the bearings by compass, it is well to commence on a definite plan. Either the actual magnetic direction can be noted, or else the true reading can be adopted by at once making the correction for the variation of the needle, which for England is now 18° 20′ west of north. In the field it is generally more convenient to take the magnetic bearings and to correct them when required for description. The variation is gradually decreasing. It attained a maximum of 24° 15′ in 1815.

the more serious work of mapping and running sections through a country, a theodolite and some experience in surveying are needed. A few small boxes, with wadding, will be found useful for friable fossils, also small bags for sands, or for separate groups of small fossils, and stores of paper for the larger and harder specimens. The rock-specimens should be trimmed, if time allow, on the spot; and should be reduced, if possible, to a uniform size, suited to the cabinet of the collector; a convenient size is three to four inches long by two to three inches broad and one to two inches thick, but this is not a matter of primary importance. Trimmed and flat specimens, however, save space and admit of readier and probably juster comparison [1].

It is further desirable that the geologist should carry with him a supply of labels, as it is most important that he should fasten on a label, or wrap one up with the specimen on the spot, and not defer it to a later period. Failing this precaution, the localities are often forgotten, and valuable specimens collected with care and difficulty become comparatively worthless. In collecting fossils, not only should the locality and geological position be given, but also, where there are several beds in the section or group, the particular bed should be entered in the note-book, and its number attached to the fossil. All notes likewise should, if possible, be made at the time, with a sketch (however rough) of the section and the thickness of each bed, together with the angle and direction of dip and strike of the beds, as well as their mineral composition. It is well also to record on the spot any general impressions and conclusions.

Besides an ordinary map of the country, the student should be provided for special work in a limited district with a map on a larger scale, such as the one-inch Ordnance or the Geological-Survey maps, mounted to fit the pocket and cut to a size suited for outdoor use.

Acids cannot be conveniently carried in the field; but, as it often is an object to distinguish limestones readily, or to test the presence of calcareous matter in other rocks (although a little experience and the use of a knife may frequently suffice), yet there are many cases where the use of dilute hydrochloric acid is necessary. Therefore, a small-capped and long-stopper bottle of such acid should be occasionally at hand. To this, for more special inquiries, may be added a small set of blow-pipe apparatus [2].

Attention has been called to the imperfection of the geological record. From the nature of the subject imperfection is inevitable, but much may be done to render it more perfect. Formerly it was considered sufficient to

[1] In many cases, especially with the igneous rocks, it is desirable to preserve a weathered surface.

[2] For many useful particulars relating to more complete Geological Surveying, see 'Field-Geology' by Messrs. W. H. Penning and A. J. Jukes-Browne.

collect the more typical specimens of a species, and to be satisfied with a general collection to represent the Formation[1]. Much more attention has, however, of late years been given to the distinction of zones; and, knowing now in how important a manner the variation of species bears upon the great question of evolution, the student should collect not only from the formation as a whole, but from every bed, and note the exact position of that bed in the series.

This is especially important where it is most difficult, as in those great homogeneous clay or calcareous deposits, such as the Oxford clay, the London clay and the Chalk, of which the component beds, throughout masses many hundred feet in vertical thickness, present nearly uniform petrological characters. For this uniformity of character, while rendering it less easy to distinguish the separate beds, shows that the physical conditions under which they were accumulated must have been nearly alike throughout the whole period of their deposition, and that consequently the changes in the forms of life are due to variations incident to lapse of time under similar or nearly similar conditions, rather than to any radical variations of the surrounding physical conditions[2]. In such instances we have length and continuity of life combined with uniformity of conditions, whereas in passing from group to group, however closely succeeding, or even from stage to stage when there is a change of lithological structure, there is either evidence of a break in time or in conditions, which, introducing a disturbing element of uncertain value, interrupts the continuity of the chain.

It is only by these means that we can hope satisfactorily to ascertain the exact series of transitional forms; and to learn whether they have been unceasingly progressive by small steps through all time, or whether the variations have been more especial and made *per saltum* at intervals of time. These, however, are questions for the biologist to decide. The geologist can only supply the evidence; and in this everything depends on its careful collection, and on accurate stratigraphical positions.

[1] The term 'Formation' is in some respects objectionable, but it is convenient, and no satisfactory substitute has as yet been proposed. I adhere to it for want of a better, and pending the Report of the Congress on Geological Nomenclature.

[2] This mode of inquiry has been applied with marked success to the Lias and the Chalk.

CHAPTER II.

THE CONSTITUENTS OF THE EARTH'S CRUST.

THE ELEMENTARY SUBSTANCES, THEIR DISTRIBUTION AND GEOLOGICAL RELATIONS. TABLE OF THESE SUBSTANCES: THEIR COMBINATIONS WITH OXYGEN AND WITH ONE ANOTHER. THEIR RELATIVE PROPORTIONS IN THE EARTH'S CRUST. THE ELEMENTS OF MOST COMMON OCCURRENCE. THE ORDINARY TESTS EMPLOYED IN THE DETERMINATION OF MINERALS. THE MINERALS AND THEIR VARIETIES FORMED BY COMBINATION OF THE MORE ABUNDANT ELEMENTS; THEIR CHEMICAL COMPOSITION AND COMMON CRYSTALLINE FORMS.

The Elementary Substances. The number of these substances at present known to enter into the composition of the crust and atmosphere of the earth amounts to sixty-four. The greater number are so rare that they only concern the chemist and the mineralogist; still it is well that the student should understand the relation of all the mineral elements one to another, and have a general knowledge of the forms under which they most usually occur.

Their Geological Relations. Except in the broad divisions of the elements into gases, non-metallic bodies or metalloids, and metals, I have not adhered to a strict chemical or mineralogical arrangement, but have adopted one in accordance with what I conceive to be better suited to the needs of the geologist, which consist in knowing the prevailing conditions under which each elementary substance is found in nature, the combinations into which these bodies respectively enter, and the form under which each is to be sought. This arrangement is given in Table I, pp. 8, 9.

In column I of this Table are given the groups into which, from the possession of certain analogous characters, the elementary substances are ranged, with modifications to meet a geological plan.

Column II contains the list of all the known elementary bodies, or simple elements, with their chemical symbols, while their specific gravity, or relative weight, is given in column III.

By far the larger number of the elements are never met with in their pure or elementary state, but exist only in combination one with another. Those which do occur pure or native are in large capitals, those which, on the contrary, are never found uncombined in nature, are in smaller capitals.

The combination most universal is that of the element with oxygen. The combinations so formed are given in column IV. When the binary substance thus produced is stable and exists native, it stands in ordinary characters; when it is unstable, and only exists in combination with other substances, it is in *italics*.

The groups of native ternary substances formed by this combination of a binary oxide with another substance or base are given in column VI. Thus for example, Calcium unites with Oxygen to form lime, but lime (1 atom calcium + 1 atom oxygen, or CaO), like the caustic alkalies, cannot exist free, and therefore unites with other substances, such as carbonic acid (1 atom carbon + 2 atoms oxygen, or CO^2), to form carbonate of lime ($CaO{\cdot}CO^2$) or calcite, or with sulphuric acid (1 atom sulphur + 3 atoms oxygen + 2 atoms water (H^2O)), to form sulphate of lime ($CaO{\cdot}SO^3 + 2\,H^2O$) or gypsum. In a similar way the metallic carbonates are formed by the union of carbonic acid with the metallic oxides (1 atom of the metal combined with one or more atoms of oxygen), in such minerals as the carbonate of iron or spathose iron-ore ($FeO{\cdot}CO^2$).

Yet more complex combinations are formed, as in the case of the Felspars, which are composed essentially of certain proportions of silica —a weak acid—(1 atom silicon + 2 atoms oxygen, or $Si\,O^2$), with alumina (2 atoms aluminium + 3 atoms oxygen, or $Al^2\,O^3$), potash (2 atoms potassium + 1 atom oxygen, or K^2O), soda (2 atoms sodium + 1 atom oxygen, or Na^2O), and lime ($Ca\,O$), the relative proportion of each binary being indicated by the addition of a numeral prefix; thus in orthoclase felspar —a double silicate of alumina and potash, in both of which one part of alumina and one of potash are combined with three parts of silica—the formula is $Al^2\,O^3{\cdot}3\,Si\,O^2 + K^2\,O{\cdot}3S\,O^2$.

A certain number of the elementary bodies are, however, found combined, not only with oxygen, but also with some of the metalloids, especially sulphur, without the intervention of oxygen. This is of frequent occurrence with the metals, as in the case of the direct combination of sulphur with iron ($Fe\,S^2$), forming the sulphuret or sulphide of iron (iron-pyrites); of sulphur with lead ($Pb\,S$), forming the sulphide or sulphuret of lead (galena); and so on with other metals of the same group. In the same way sodium combines directly with chlorine, forming chloride of sodium or common salt ($Na\,Cl$), and carbon with hydrogen forming the various hydro-carbons. These other substances forming binary compounds with the element in col. II are given in col. V; the compounds they form in nature will be found in col. VI.

The combinations of some of the rarer metals, as weak acid oxides, with other metals are of no geological importance, but are given to show the place in nature of these substances, and the forms under which they generally occur.

TABLE I.

I. *General Divisions.*	II. *The Elementary Substances and their Chemical Symbols.*	III. *Specific Gravity.*	IV. *Binary Combination of the Element with Oxygen.*	V. *Other bodies with which the Element forms direct binary combinations.*	VI. *Combinations in which the Elementary Bodies most commonly occur in nature.*
Gases.	OXYGEN .... O.	1·1056	(Ozone)	.. ..	*Passim* (see Col. IV.)
	[1] NITROGEN .. N.	0·9713	Air		
	HYDROGEN .. H.	0·0691	Water (H^2O)	Carbon	The Hydro-carbons.
Other Non-Metallic Substances or Metalloids.	CARBON .... C.	2·27	.. ..	.. ..	Native (see p. 22).
			Carbonic acid (Carbon dioxide CO^2)	.. ..	Carbonates of various Earths and of Metallic Oxides.
			.. ..	Hydrogen	Various Hydro-carbons.
	SULPHUR .... S.	1·98	.. ..	.. ..	Native.
			Sulphuric acid (H^2SO^4)	.. ..	Sulphates of some Earths and Alkalies (pp. 19, 22).
			.. ..	Various Metals (see p. 9) ..	Sulphurets or Sulphides of those Metals.
	SILICON........ Si.	2·34	Silica (SiO^2) .. .	.. ..	Various forms of Quartz.
				.. ..	Silicates of the Earths, Alkalies, and some Metallic Oxides.
	PHOSPHORUS ... P.	1·84	*Phosphoric acid* (P^2O^5)	. . ..	Phosphates of some Earths, and of a few Metallic Oxides.
	BORON .... B.	2·63	*Boric oxide* (B^2O^3)	.. ..	With water, as Boracic Acid, forming Borates of some Alkalies and Earths.
	[2] CHLORINE .... Cl.	2·470	None native	Sodium, Potassium .. .. Silver, Mercury	Chlorides of these Metals.
	FLUORINE...... F.	0·987	None	Calcium ; Al.	Fluorides of Calcium and Aluminium.
	IODINE . . .... I.	4·95	None native	Sodium, Magnesium .. .. Silver, Mercury	Iodides and Bromides of these Alkalies (in sea-water) and Metals.
	BROMINE ...... Br.	3·00			
	SELENIUM...... Se.	4·28	No native combination	Lead, Bismuth. Copper, Silver,	Native and as Selenides and Tellurides of these Metals.
	TELLURIUM .... Te.	6·24			
Metals of the Alkalies.	POTASSIUM .... K.	0·86	*Potash* (K^2O) ..	.. ..	Forms with the Earths the bases of various Silicates.
			.. ..	Chlorine.. .	Chlorides in sea and mineral waters, and in Rock-salt.
	SODIUM........ Na.	0·97	*Soda* (Na^2O) ..	. .. .	Forms with the Earths the bases of various Silicates.
			.. ..	Chlorine.. ..	Chlorides in sea and mineral waters, and in Rock-salt.
	LITHIUM ...... Li.	0·59	*Lithia* (LiO) . ..	. . ..	In a few Silicates.
	CÆSIUM ...... Cs.	.. ..	.. ..	.. ..	Little known and rare.
	RUBIDIUM ...... Rb.	1·52	.. ..	.. ..	In a few mineral waters.
Metals of the Alkaline Earths.	BARIUM........ Ba.	4·00	*Barytes* (BaO) ..	.. ..	Carbonates and Sulphates.
	STRONTIUM .... Sr.	2·54	*Strontia* (SrO)	.. ..	
	CALCIUM ...... Ca.	1·58	.. ..	.. ..	Fluoride of Calcium.
			Lime (CaO)	.. ..	Lime as a Sulphate; Lime and Magnesia as Carbonates; Lime and Alumina as Phosphates; and all as joint bases with the Alkalies in numerous Silicates.
Metals of the Earths.	MAGNESIUM .... Mg.	1·74	Magnesia (MgO)	.. ..	
	ALUMINIUM .... Al.	2·56	Alumina (Al^2O^3)		
			.. ..	Fluorine.. ..	Fluoride of Aluminium.
	GLUCINUM .... Gl.	2·10	*Glucina* (GlO) ..	.. ..	As a Silicate with Al.

[1] In air, Nitrogen and Oxygen are mechanically mixed in the proportion of 79 of the former to 21 of the latter. The chemical combinations of Nitrogen with Oxygen form corrosive acids of no importance to the geologist.

[2] Chlorine and the five elements following, with the exception of Fluorine, form artificial combinations with Oxygen, but are not known as natural products. They also all combine with Hydrogen; but the only combination interesting to geologists is the one with Chlorine, forming hydrochloric acid in Volcanic emanations.

I. *General Divisions.*	II. *The Elementary Substances and their Chemical Symbols.*	III. *Specific Gravity.*	IV. *Binary Combination of the Element with Oxygen.*	V. *Other bodies with which the Element forms direct binary combinations.*	VI. *Combinations in which the Elementary Bodies most commonly occur in nature.*
Metals of the Earths.	ZIRCONIUM .... Zr.	.. ..	*Zirconia* (ZrO^2)	.. ..	As Silicates of these Earths.
	THORIUM ..... Th.	.. ..	*Thoria* (ThO)		
	YTTRIUM ..... Y.	.. ..	*Yttria* (YO)	.. ..	Part bases of a few rare Silicates.
	ERBIUM ..... Eb.	.. ..	*Erbia* (EbO)		
METALS PROPER.	GOLD .... Au.	19·26			
Found Native, or in a Metallic State.	PLATINUM .. Pt.	21·50	.. ..	.. ..	Native, or combined with one another and with a few other metals as alloys.
	PALLADIUM .. Pd.	11·80			
	IRIDIUM .... Ir.	21·15			
	RHODIUM ... Rh.	11·00			
	OSMIUM .. Os.	21·40			
	RUTHENIUM . Ru.	12·60			
Often found Native.	SILVER[1] .. .. Ag.	10·57	*No Native oxides*	Sulphur, Chlorine, Iodine, some Metals	Sulphurets or Sulphides, Chlorides, &c., Alloys.
	MERCURY.... Hg.	15·60			
	COPPER .... Cu.	8·94	suboxide; protoxide (Cu^2O, CuO)	.. .. Sulphur, Chlorine	Red and black Oxides; Carbonates, Silicates, &c. Sulphuret, Chloride.
	BISMUTH .. Bi.	9·80	*No Native oxides*	.. .. Sulphur, Tellurium	Carbonate, Silicate, &c. Sulphuret, Telluride.
Occasionally found Native.	ARSENIC .... As.	5·63	protoxide (As^2O^3)	.. .. .. Sulphur, various Metals	Oxide; Arseniates. Sulphurets, Arsenides.
	ANTIMONY .. Sb.	6·72	protoxide (Sb^2O^3)	.. .. Sulphur .. .	Antimonates. Sulphurets.
Very rarely found Native.	LEAD .... Pb.	11·33	protoxide (PbO) .. peroxide (PbO^2)	.. .. Sulphur .. .	Oxides; Carbo-Sulphate, Phosphate, &c. Sulphuret.
	ZINC......... Zn.	7·13	oxide (ZnO)	. .. .	Oxide; Carb. Sil., &c. Sulphuret.
	IRON[2] ..... Fe.	7·84	protoxide (FeO) .. peroxide (Fe^2O^3)	.. .. Sulphur.. ..	Oxides; Carbonates, Phosp. Silicates, &c. Sulphurets.
	TIN .... Sn.	7·30	peroxide (SnO^2)	.. .. Sulphur	Oxide. Sulphuret.
Metals never found in a metallic state.	MANGANESE.... Mn.	8·02	sesquioxide (Mn^2O^3) peroxide (MnO^2)	.. .. Sulphur	Oxides, Carb. Sil., &c. Sulphuret.
	COBALT...... Co.	8·51	oxide (CoO)	.. .. Sulphur; Arsenic	Oxide?; Arseniate. Sulphurets; Arsenide.
	NICKEL...... Ni.	8·82	oxide (NiO)	.. .. Sulphur; Arsenic	Oxide?; Arseniate. Sulphurets; Arsenide.
	CADMIUM ..... Cd.	8·45	*No Native oxide* ..	Sulphur	Sulphuret.
	MOLYBDENUM .. Mo.	8·63	.. .. *No Native oxide*	Sulphur	Sulphuret. Molybdates.
	TITANIUM .... Ti.	5·30	peroxide (TiO^2) ..	Oxides of these metals form weak acids which are found in combination with certain metallic oxides, such as those of Iron, Lead, Copper, or Manganese, and some with Lime.	Oxide; Titanates.
	URANIUM .... U.	18·40	protoxide (U^3O^4) ..		Oxide; Uranates.
	CHROMIUM .... Cr.	7·01	? sesquioxide (Cr^2O^3)		Oxide?; Chromates.
	TUNGSTEN .... W.	18·30	peroxide (WO^3) ..		Oxide; Tungstates.
	VANADIUM .... V.	.. ..	*No Native oxide* ..		Vanadates.
	TANTALUM .... Ta.	6·78	Ditto. ..		Tantalates.
	COLUMBIUM, .. Cb. or NIOBIUM, .. Nb.	.. ..	Ditto.		Columbates.
	CERIUM....... Ce.	5·50	Ditto	.. ..	Rare Metals occurring together in some Silicates and Phosphates.
	DIDYMIUM .... Di.	.. ..	Ditto		
	LANTHANUM .... La.	.. ..	Ditto		
	THALLIUM...... Tl.	11·90	. .. .	.. ..	Rare and little known Metals, found with Sulphides of Iron, Copper, and Zinc.
	GALLIUM .... Ga.	.. ..			
	INDIUM .... In.	7·36			

[1] Constantly found in combination with Gold and Lead.
[2] Iron combined with a small proportion of Nickel is commonly found native in Meteorites. There is some doubt about the occurrence of native terrestrial Iron; in any case grains of it are of extreme rarity in some Basalts. (See p. 22.)

The most abundant Elements. Notwithstanding the number of these elementary substances, and in strong contrast with the infinite variety of combination into which the three gases alone, in conjunction with carbon, enter to form the almost innumerable *organic* substances elaborated by living tissues, the number of definite *inorganic* combinations formed by the whole of the 64 elements is comparatively small. At present the number of known minerals resulting from these combinations does not exceed about 600. The greater part of these are also of such exceptional occurrence that they do not concern the ordinary geologist. It is essential for him, however, to be acquainted with those more abundant minerals which form the constituents of the crystalline and sedimentary rocks.

This number is comparatively limited, only 11 out of the 64 elementary substances entering largely into the composition of the rocks forming the crust of the earth, and it is with their combinations alone that the geologist has mainly to deal. It has been estimated that these 11 elementary substances constitute 99 out of every 100 parts of the earth's crust, and the proportion in which they there exist, in combination one with another (assigning to that crust a thickness of 60 miles), has been roughly estimated to be in the following ratio.

TABLE II.

ESTIMATED PERCENTAGE OF THE ELEMENTS IN THE EARTH'S CRUST.

A. *The simple Elements with Oxygen separate.*			B. *The same with the Oxygen in combination.*		
1.	Oxygen	50·0	I.	Silica	53·0
2.	Silicon	25·0	II.	Alumina	19·0
3.	Aluminium	10·0	III.	Lime	6·3
4.	Calcium	4·5	IV.	Magnesia	5·8
5.	Magnesium	3·5	V.	Soda	2·5
6.	Sodium	2·0	VI.	Potash	2·4
7.	Potassium	1·6	VII.	Carbonic Acid	7·5
8.	Carbon	2·4	VIII.	Iron-Oxides	
9.	Iron		IX.	Sulphuric acid	
10.	Sulphur		X.	(Chlorides)	
11.	Chlorine		XI.	Other bodies	3·5
12.	Other bodies	1·0			100·0
		100·0			

Taking the oxidised elements under B in the above list in the order of their relative abundance, the more common minerals formed by them alone, or in combination amongst themselves, are briefly described in the following pages.

To recognise the more common of these minerals and rocks, a few

simple tests are required, by which such of their distinctive properties, as those of hardness, specific gravity, streak, solubility, fusibility, and chemical reaction, may be easily determined.

Hardness. The degree of 'hardness' of a mineral has reference to the numbers in a scale, in which certain well-known minerals form the standards of comparison, in the following order, beginning with the softest. For this purpose, the crystallised varieties should be selected [1].

	Hardness.		*Hardness.*
Talc, laminated	1	Scapolite	5·5
Gypsum or Selenite	2	Felspar (Orthoclase)	6
Mica	2·5	Quartz (Rock-crystal)	7
Calcite	3	Topaz	8
Fluor Spar	4	Corundum (Sapphire and Ruby)	9
Apatite	5	Diamond	10

Specific Gravity. To obtain the 'specific gravity' or density (relative) of a mineral or rock, it is only necessary to compare its weight with that of an equal bulk of distilled water (which is taken as unity) at a temperature of 60° Fahr. This may be done in two ways.

In the first and most usual method, use is made of a delicate balance, weighing fractions of grains, and having one short and one long scale (Fig. 1 *a*). The mineral or rock is suspended from a hook under the pan of the short scale by a hair or fibre of silk, and first weighed in the ordinary way. A tumbler of distilled water at 60° is then placed under this scale, and the weight of the rock or mineral when immersed in the water (care being taken that it is perfectly immersed) again determined. The weight of the mineral in air, divided by the loss of weight in water, gives its specific gravity.

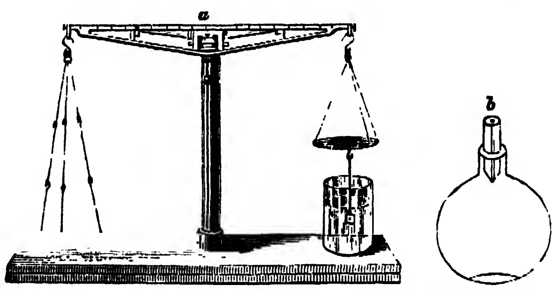


FIG. 1.—*a*. Specific Gravity Balance. *b*. Specific Gravity Bottle.

For example:—

Weight of crystal or rock in air	293·7 grains
Weight when immersed in water	180·1 "
Difference being weight of an equal volume of water	113·6 grains.

The 293·7 divided by 113·6 = 2·59, the specific gravity required.

[1] Small boxes containing these test specimens are sold by the dealers in minerals. For the other experiments named here, all that the beginner requires is a blowpipe with a lamp or candle, some small lengths of platinum wire, a small forceps with platinum tips, a few pieces of charcoal, the ordinary fluxes, some open and closed glass tubes and watch-glasses, a knife, a file, a small loadstone, a bottle of strong and one of dilute hydrochloric acid, and a magnifying glass.

In the other plan, which is convenient especially for porous minerals and rocks, use is made of a light glass bottle with a perforated glass stopper (Fig. 1 *b*), holding a given quantity, say 1000 grains, of distilled water at 60° and weighed. The specimen, pounded or in powder, is first weighed in the open air and then introduced into the bottle, and the overflowing water, together with that which escapes when the stopper is inserted, carefully wiped off. The bottle is now weighed again—the difference in weight being the weight of the water displaced. The weight of the specimen divided by the weight of the water displaced gives the specific gravity of the substance[1].

In all cases care must be taken to avoid air-bubbles interfering with the substance immersed.

In the determination of minerals, specific gravity has a definite and exact value; but in its application to rocks it has, owing to their variable composition, a wider range. Still, within certain limits, it has considerable value.

Streak. The 'streak' is the colour left by the mineral when rubbed on a hard surface. An unglazed porcelain tablet or file is convenient for this purpose: or the powder produced by a steel knife scratch will serve.

Solubility. The 'solubility' has reference to the action of acids,—generally hydrochloric acid diluted with one-half or two-thirds of water by measure; in some cases it is necessary to powder the mineral and to use strong acid to obtain a proper action[2].

Fusibility. The 'fusibility' relates to the action of the blowpipe on a small portion of the mineral, either a splinter held in the platinum forceps, or a little of it placed on charcoal.

The re-actions with the blowpipe are obtained by fusing a small fragment or the powder of the mineral on the looped end of a short length of platinum wire, or on a piece of charcoal, with borax or microcosmic salt. A bead is produced varying in tint according to whether it has been subjected to the reducing or the oxidising flame of the blowpipe, and assuming definite colours in accordance with the mineral substance present. The student will find all the necessary information on this subject in works on the Blowpipe and in text-books on Chemistry. For the many varieties and physical properties of minerals, he must refer to special works on Mineralogy and Petrology.

The groups of minerals formed by the several elementary substances, after combination with Oxygen, of most importance to the geologist are:—

I. **SILICA.**—This, the most abundant of all the constituents of rocks, occurs native in various forms, which possess, when pure, the following characters:—*Infusible before the blowpipe, insoluble*

[1] Jolly's spring balance is more portable and of quicker use, but is not of the same accuracy.

[2] A few substances, such as rock-salt, dissolve in water.

in acids, strikes fire with iron, scratches glass, and is not scratched by a knife; fracture conchoidal: hardness = 7; Sp. Gr. = 2·6—2·7.

The commoner forms of silica are as follows:—

Quartz.—Silica in a pure state; crystallised it is known as rock-crystal (Fig. 2), forming six-sided prisms, terminating at one or both ends in six-sided pyramids. Colourless when pure.

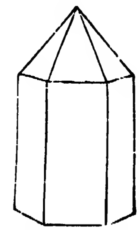


FIG. 2.—Rock Crystal.

When slightly tinted purple, rock-crystal is known as *Amethyst*.

When slightly tinted yellow and shades of brown, rock-crystal is known as *Cairngorum*.

Chalcedony.—A semi-transparent, waxy-looking form of quartz—botryoidal—usually deposited in cavities of rocks, of flints and geodes, concretionary, massive or crypto-crystalline.

The milky and reddish varieties constitute—*Carnelian*.

Arranged in coloured concentric bands—*Agate*. A variety with coloured horizontal bands—*Onyx*.

Coloured of a uniform apple-green—*Chrysoprase*.

Flint.—A massive dark-coloured or black [1], semi-translucent, dull-looking variety of silica; burns, when pure, opaque-white; fracture conchoidal.

Yellow or brown with a splintering horny fracture—*Chert*.

Jasper.—Opaque-red, brown, or green (owing to the presence of variable small proportions of alumina and iron); often banded.

Dark green, spotted with red, constitutes—*Bloodstone*.

Velvet black with smooth fracture—*Lydian Stone*.

Another subsection of silica consists of the hydrated varieties of silica, *i.e.* silica combined with 5 to 12 per cent. of water. These minerals have a resinous or vitreous lustre, with a conchoidal fracture, and are less hard and heavy than anhydrous silica. They consist of:—

Opal.—Translucent or semi-opaque, white or light brown at times, with iridescent colours. H = 5·5—6·5; Sp. Gr. 2·2.

Whitish, translucent in water—*Hydrophane*.

Fossil wood in which the woody fibre is replaced by vitreous-looking silica—light-coloured or brown, is known as—*Wood-Opal*.

Menilite.—Opaque, brown, flattish concretions, coated white.

Siliceous Sinter.—Generally friable, often porous, of various shades of white,—deposited by hot springs.

Anhydrous Silicates.—Silica enters, in variable proportions, into combination with the various earths and alkalies, and thus forms the chief constituent in the silicates which enter so largely into the composition of the igneous and metamorphic rocks.

The most important of these silicates are the felspars, which consist of silica combined with *Alumina, Potash, Soda,* and *Lime*. They are divided into—

Potash-Felspars. Orthoclase (common felspar). Fig. 3*a*. Colour generally opaque-white, grey, or light red. H = 6; Sp. Gr. = 2·4—2·6. Lustre vitreous or pearly.

Composition.

Silica	64·7	or $Al^2O^3 \cdot 3SiO^2 + KO \cdot 3SiO^2$.
Alumina	18·4	
Potash	16·9	
	100·0	

[1] A colour generally due to the presence of a small quantity of organic matter or carbon.

Crystalline form.—Modified oblique rhombic prism.

This is the most abundant of all the felspars.

Varieties:—*Adularia* (and *Moonstone*), *Amazon Stone*, *Sanadine*, or glassy felspar.

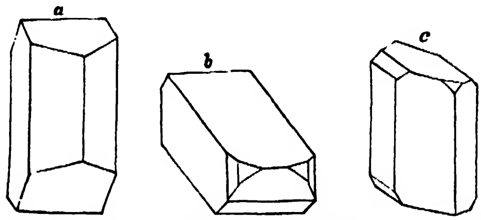


FIG. 3.—Felspars. *a. Orthoclase; b. Albite; c. Anorthite.*

Soda-Felspars.—Albite (Fig. 3 *b*), which contains no lime, and is colourless or of light colours, is the typical form of the soda-felspars, but the more common form is **Oligoclase,** of which the colours are light grey, yellow, or greenish: H = 6—7; Sp. Gr. = 2·65—2·7, and—

Composition.

Silica	61·9	or $2Al^2O^3 \cdot 2SiO^2 + RO \cdot 3SiO^2$. (R represents the variable bases — Lime, Soda, etc.).
Alumina	24·1	
Soda	8·8	
Lime	5·2	
	100·0	

Crystalline form.—Oblique rhomboidal prism.

Lime-Felspars.—Anorthite (Fig. 3 *c*), which, colourless or white, is the type lime-felspar, containing no soda, is a comparatively rare form. The important rock-constituent of this section is **Labradorite,** grey, greenish, bluish. Polished specimens often beautifully iridescent. Lustre vitreous. H = 6; Sp. Gr. 2·7—2·76.

Composition.

Silica...	52·9	or $Al^2O^3 \cdot 2SiO^2 + RO \cdot SiO^2$.
Alumina	30 3	
Lime...	12·3	
Soda	4·5	
	100·0	

It occurs commonly in cleavable masses; crystallises in double oblique rhomboidal prisms.'

The composition of all the felspars is liable to vary, by the partial replacement of the alkaline bases by one another. They all weather under the action of the air and rain, decomposing and losing their colour (often forming a white coating); but Albite is less liable to this change than the other varieties of felspar.

Felspars are fusible (more or less) before the blowpipe, are scratched by quartz, and usually exhibit marked cleavage. They may be distinguished from one another by the lime-felspars being soluble in heated hydrochloric acid. whereas the soda and potash-felspars are insoluble. The soda-felspars colour the blowpipe flame yellow, and are more fusible than the potash-felspars.

The potash-felspars are *monoclinic*, while the soda- and lime- or the plagioclase felspars are *triclinic*; that is to say, the former have two principal cleavage-planes at right angles to one another, and one oblique axis; whereas in the latter all three axes or planes are oblique to one another. The triclinic felspars may generally be distinguished by their fine striation on the basal cleavage-plane; or by exhibiting alternate bands of colour in a thin section under polarised light.

Amongst the common minerals allied in composition to the felspars are Leucite (white garnet, same form as Fig. 6 *a*) and Nepheline; they may be recognised by their crystalline forms, and by the former decomposing and the latter gelatinising in hydrochloric acid.

Silica in combination with other bases.

Mica (Muscovite), Potash mica (Fig. 4 *a*).—This mineral is readily distinguished from all others by the great facility with which it cleaves or splits into thin elastic laminæ, in lines parallel to the basal plane. H = 2—2·5 ; Sp. Gr. = 2·75—3·1.

It consists essentially of—

Silica	46·3	
Alumina	36·8	
Potash	9·2	$3Al^2O^3 \cdot SiO^2 + KO \cdot 3SiO^2$.
Iron-peroxide	4·5	
Other bases and water	2·4	
	100·0	

Crystalline form.—Oblique rhombic prisms, with a basal cleavage very perfect.

The other occasional bases consist of small variable proportions of ***Lithia***, ***Magnesia***, or ***Fluorine***; but lime is never present, and soda rarely. Mica is a soft mineral, and it has a brilliant pearly lustre. The colours are shades of white, yellow, brown, red, and black. Translucent; not soluble in acids; whitens and fuses slightly before the blowpipe.

FIG. 4.—Mica. *a. Muscovite*; *b. Biotite.*

Varieties :—*Lepidolite* (Lithia-Mica); *Biotite* (Fig. 4 *b*, Magnesia-Mica).

Silicates in which Iron oxides and Magnesia more or less replace Alumina.

Hornblende (Amphibole). Fig. 5 *a*.—In this important group of Silicates, magnesia, lime, and the protoxide of iron form the essential and variable bases. Hardness = 5—6 ; Sp. Gr. 2·9—3·4. Colour green to black; fracture uneven; lustre vitreous: transparent to opaque: streak greenish grey.

Composition.

Silica	48·8	
Magnesia	13·6	
Lime	10·2	
Alumina	7·5	(CaO·FeO) SiO^2.
Protoxide of Iron	18·75	
Manganese	·15	
Other substances and water ...	·9	
	99·9	

Crystallises generally in oblique rhombic prisms, more or less modified, and often slender and acicular.

Tough and heavy. Fuses before the blowpipe into a black bead. The bases variable. Iron is rarely present, or only in small proportion, in the following varieties :—

Actinolite—Bright green and glassy. No alumina and little iron. In slender prisms, which often form radiating masses.

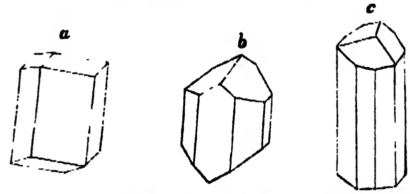


FIG. 5.—*a. Hornblende*; *b. Augite*; *c. Tourmaline*

Tremolite—White or grey crystals, long and blade-like; sometimes fibrous, sometimes massive. Both iron and alumina absent.

Asbestos is a fibrous form of these two varieties of the Amphibole group.

Augite or **Pyroxene** (Fig. 5 *b*).—Closely allied to hornblende. Colour grey, green, and black. Opaque; lustre vitreous. Streak white or light grey. Crystals small: of frequent occurrence in lavas. H = 5—6 ; Sp. Gr. = 3·2—3·5.

	Composition.	
Silica	47·63	(CaO·MgO·FeO) SiO^2.
Lime	20·87	
Magnesia	12·9	
Alumina	6·74	
Protoxide of Iron	11·39	
Protoxide of Manganese	0·21	
Water	0·28	
	100·02	

Crystallises in modified oblique rhombic prisms.

Fuses into a glass before the blowpipe. Augite is more common in volcanic, and Hornblende in plutonic rocks. The former rarely associated with quartz, the latter often. They both vary greatly in the proportion of iron-oxide and other bases present in the varieties. The crystals of augite are usually thick and stout: those of hornblende are more columnar and fibrous, and show distinct prismatic cleavage.

Diallage—A thin foliated variety, clear-green colour, translucent, common with bronzite in serpentine. Lustre pearly.

Nearly allied to the preceding silicates are—

Tourmaline (Fig. 5 *c*).—Colour usually black or some shade of green or black; rarely pink; slightly translucent; usually crystallises in long prisms with convex sides and strongly furrowed. This is a silicate of alumina with a certain proportion of *boracic acid* and variable proportions of iron, manganese, potash, soda, or lithia. Electric when heated. Used for polarising instruments. H = 7—7·5; Sp. Gr. = 3—3·3. Is distinguished from hornblende by its more resinous fracture and the absence of cleavage.

Variety:—*Schorl*—Black and opaque. Common in some Cornish and other granites.

Another important group of the compound anhydrous silicates is that of the—

Garnets (Fig. 6 *a*).—Essentially silicates of alumina and lime, with magnesia, the oxides of iron, *manganese*, and *chromium*.

The crystalline form is usually a dodecahedron (Fig. 11 *b*) or trapezohedron (6 *a*); but garnet is also found massive. Colour commonly red, but sometimes brown, black, green, and even white. Transparent. Streak whitish. Hardness = 6·5—7·5; Sp. Gr. = 3·15—4·3. All varieties fuse more or less readily before the blowpipe—a property common to idocrase (Fig. 6 *b*) and epidote, which are closely allied in mineral composition and in geological relations, but differ in form. Common in metamorphic and present in some igneous rocks.

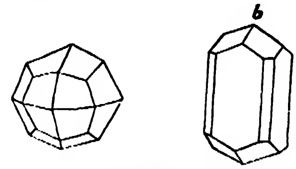


FIG. 6.—*a. Garnet*; *b. Idocrase.*

Silicates of Magnesia with variable proportions of Iron and Manganese.

These silicates constitute a small but important geological section.

Olivine (Peridot). Glassy, translucent: light olive or yellowish green. Common as embedded grains in basalt. Crystallises in right rectangular prisms. Scratches glass and is scratched by quartz. Sp. Gr. 3·3—3·5.

	Composition (*specimen from Somma*).	
Silica	40·08	$(MgO·FeO)^2 Si·O^2$.
Magnesia	44·24	
Protoxide of Iron	15·26	
Protoxide of Manganese	0·48	
Alumina	0·18	
	100·24	

Enstatite.—A light-coloured silicate of magnesia. Lustre pearly. H = 5·5; Sp. Gr. = 3·1—3·3.

Bronzite—A ferruginous dark-green or brown variety with a submetallic or bronze-like lustre.

Hypersthene.—Colour brownish-green to black. H = 5—6; Sp. Gr. = 3·39. Translucent or opaque; fuses to a black enamel.

Composition.

Silica	54·2	(MgO.FeO) Si O^2.
Magnesia	24·1	
Iron-protoxide	21·7	
	100·0	

None of the anhydrous magnesian silicates gelatinize with acids.

The Hydrous Silicates. The most important of these to the geologist are the magnesian silicates, all of which are greasy or soapy to the touch. The principal minerals of this group are,—

Talc.—White, grey, and green; translucent; lustre pearly; infusible; not decomposed by acids. Foliated; flexible; but not elastic. H = 1—1·5; Sp. Gr. = 2·6—2·8.

Composition.

Silica	63·49	6 MgO·5SiO^2 + 2H^{2}O.
Magnesia	31·75	
Protoxide of Iron and Water ...	4·76	
	100·00	

Steatite (Soap-stone, 'French-chalk'), a massive amorphous variety.

Chlorite.—Various shades of dark green; translucent; soft; foliated; and granular. H = 1·5; Sp. Gr. = 2·65—2·85.

Composition.

Silica	31·47	2(2RO·SiO^2) + Al^{2}O^3 + 3H^{2}O.
Magnesia	32·56	
Alumina	16·67	
Protoxide of Iron	5·97	
Water	12·42	
	99·09	

Fuses with difficulty at the edges. Distinguished from talc by giving off water when heated in a glass tube.

It is the characteristic ingredient in Chlorite-slate.

Serpentine.—Various shades of green, sometimes red; translucent or opaque. H = 2·5—4; Sp. Gr. = 2·5—2·65. Amorphous and massive. When pure, essentially a hydrous silicate of magnesia, in which the silica is in less proportion than in talc[1].

Nephrite (**Jade**).—A very slightly hydrated silicate of magnesia and lime, with a little alumina and iron. By some mineralogists this mineral is placed in this group and by others with the Amphibole group. Some varieties are silicates of lime and magnesia, almost identical with Tremolite; while others contain alumina, and are more related to Prehnite, worked objects of which often pass under the name of jade.

H = 6·5—7·5; Sp. Gr. = 2·9—3·1.

Colour whitish with more or less green. Infusible; translucent; lustre vitreous; fracture splintery; very tough. Much used for stone implements.

Another section of silicates, distinguished by the large proportion of water they contain, are the

[1] By many geologists this is now looked upon as a hydrated olivine rock.

Zeolites, all of which have certain characters in common. They are mostly milky-white and semi-transparent; occasionally red. Before the blowpipe they intumesce (hence the name), and melt into a cloudy glass. They are decomposed and mostly gelatinised by hydrochloric acid. Their specific gravity varies from 2—2·7, and hardness = 3·5. They consist of silicates of alumina and lime; sometimes with small proportions of alkalies, but always with water, often in the proportion of 16 to 18 per cent.

The chief minerals of this group are,—

Heulandite.	*Analcime.*	*Chabasite.*
Stilbite.	*Natrolite.*	*Prehnite.*

These are of common occurrence lining cavities in lavas and basalts, and as amygdaloids. They rarely occur in other rocks.

Hydrous Silicates of Iron.—The most common of these are the small green grains known as **Glauconite.** These consist essentially of silicates of iron and potash, with variable proportions of magnesia, lime, and alumina, and with 6 to 12 per cent. of water. Colour olive-green and blackish green, opaque. H = 2; Sp. Gr. = 2·2—2·4. These dark-green grains form an abundant ingredient in many sands and sandstones of Primary, Secondary, and Tertiary age.

Viridite is probably a product of the decomposition of olivine.

Green-earth is mostly a product of the decomposition of augite and hornblende.

II. **ALUMINA. Corundum** (Fig. 7 *a*) is a pure crystallised form of alumina; translucent or opaque; colour generally yellow, brown, pink, or blueish. H = 9; Sp. Gr. = 3·9—4·6. Infusible and insoluble. Crystallises in six-sided prisms, with uneven surfaces and flat ends.

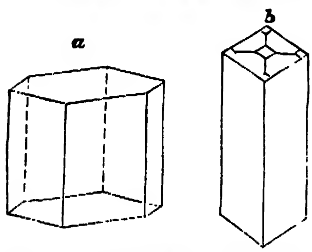


FIG. 7.—*a. Corundum; b. Chiastolite.*

The clear and blue varieties of this mineral constitute *Sapphire*; and the red, *Oriental Ruby*; the dark opaque impure varieties, *Emery*.

Alumina is also the chief ingredient in **Andalusite**, a variety of which, *Chiastolite* (Fig. 7 *b*), is very common in some slates in the form of long light-coloured crystals showing a tessellated structure on the cross fracture.

Alumina also occurs as a hydrate in **Bauxite**; as a hydrous sulphate in **Websterite**; as a hydrous phosphate in **Wavellite**; and as a fluoride of aluminium and sodium in **Cryolite.** It is from cryolite and bauxite that the greater part of the aluminium of commerce is now obtained.

Alumina is the basis of all clays. In some earthy minerals, the presence of alumina causes them to adhere to the tongue.

III. **LIME.**—This does not form a stable compound, but is always found in combination with other substances.

Calcite, or calcareous spar, is a carbonate of lime. When pure it is transparent and colourless; and is the most common of all spars and crystals in the sedimentary strata. H = 3; Sp. Gr. = 2·5—2·8. It is easily scratched with a knife. It dissolves entirely in dilute hydrochloric acid, with strong effervescence. It crystallises in a very great number of forms, amongst the commonest of which are,—

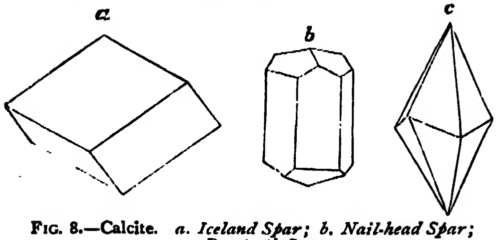


FIG. 8.—Calcite. *a. Iceland Spar; b. Nail-head Spar; c. Dog-tooth Spar.*

1. Rhombohedrons, exhibiting double refraction. Iceland spar (Fig. 8 *a*) is the pure, transparent form. 2. Scalenohedron, known as Dog-tooth Spar (Fig. 8 *c*). 3. Hexagonal prisms, known as Nail-head Spar (Fig. 8 *b*).

The following are varieties of calcareous spar or calcite:—

Satin-spar.—A fibrous opaque structure, with a satiny lustre.

Stalactite.—Semi-crystalline, translucent,—pendant in caves.

Stalagmite.—Semi-crystalline, translucent, tabular,—covering floor of caves.

Travertine is a calcareous deposit from springs, called also calc-tuff or calcareous tufa.

Aragonite is another form of carbonate of lime, crystallising in a different system—rhombic prisms. It is slightly harder and heavier than ordinary calcite, from which, however, it does not differ in composition. Falls to powder before the blowpipe. It often occurs fibrous, and in stellate masses. H = 3·5—4; Sp. Gr. = 2·93.

All carbonates of lime effervesce when touched with dilute hydrochloric acid.

Selenite or **Gypsum** (Fig. 9 *a*) is a sulphate of lime.—Crystallises in right rhomboidal prisms, cleaving with great facility parallel with the basal plane. H = 1·5—2; Sp. Gr. = 2·3—2·33. It is easily cut with a knife, and is generally limpid and translucent. Does not effervesce with acids.

Composition.

Lime	32·6	$CaO{\cdot}SO^3 + 2H^2O$.
Sulphuric Acid	46·5	
Water	20·9	
	100·0	

The varieties of Gypsum are,—

Alabaster.—Amorphous, translucent, white, easily carved. Is distinguished from calcite and its varieties by its lesser hardness and its insolubility in acids. Gypsum, when exposed to a strong heat, loses its water of crystallisation, becomes opaque and white, and forms the substance known as Plaster-of-Paris, which on reabsorption of water, rapidly hardens and sets.

Satin-spar.—This term is also applied to a white fibrous variety of gypsum, with a silky lustre.

Anhydrite.—The anhydrous or waterless form of sulphate of lime; crystallises in rectangular prisms; but is usually found amorphous and massive, granular and lamellar. Colour white, or tinged with grey, blue, or red. Lustre more or less pearly. H = 3—3·5; Sp. Gr. = 2·9—3. Before the blowpipe becomes white, but does not exfoliate like gypsum. Soluble in hydrochloric acid. Occurs in beds with gypsum, associated with rock-salt, and in various limestone strata.

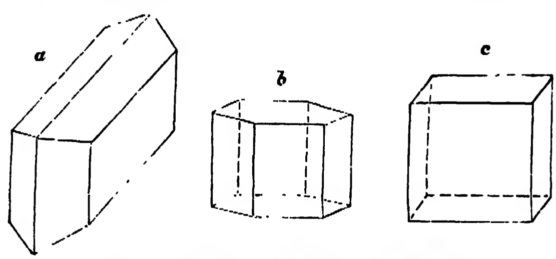


FIG. 9. *a. Selenite; b. Apatite; c Fluor-spar.*

Apatite (Fig. 9 *b*) is a phosphate of lime with chloride or fluoride of calcium. Crystallises in hexagonal prisms; colour of various shades, chiefly pale greens; transparent to opaque. H = 5; Sp. Gr. = 2·9—3·2. Infusible; slowly soluble in nitric acid.

Composition.

Lime	49·65	$3(Ca^3P^2O^8) + CaF^2$.
Phosphoric Acid	41·48	
Fluo-Chloride of Calcium ...	8·87	
	100·00	

Phosphorite is a massive, amorphous, concretionary, and mammillated variety, often with a fibrous structure. *Coprolites* are dark concretionary nodules of impure phosphate of lime, commonly of organic origin, occurring in many sedimentary strata.

Fluor-spar (Fig. 9 *c*), the metallic base of lime (calcium) combined with fluorine. This beautiful substance, which crystallises in cubical transparent crystals, is colourless or of various shades of

green, yellow, and purple; lustre vitreous. Common in mineral veins. H = 4; Sp. Gr. = 3—3·25. Fuses before the blowpipe on charcoal.

Composition.

Calcium	51·87	Ca F.
Fluorine	48·15	
	100·00	

Lime is found combined with silica in **Wollastonite** (Tabular Spar), a white or light-coloured mineral, with vitreous lustre; usually massive; cleaving easily in one direction. Occurs in granites and metamorphic limestones. H = 4·5; Sp. Gr. = 2·8—2·9.

Composition.

Silica	52·0	$3CaO{\cdot}2SiO^2$.
Lime	48·0	
	100·0	

Lime is a common ingredient in almost all sedimentary formations, whether as a cementing material or forming rocks of various textures, such as,—

Limestone and *Marble.*—Hard, variously coloured, sub-crystalline or amorphous carbonate of lime, more or less impure.

Oolite.—Compact, light-yellow and grey carbonate of lime, often in the form of small rounded grains, like the roe of a fish; at other times consisting of small comminuted fragments of shells.

Chalk.—A white, earthy, nearly pure carbonate of lime.

Marl.—A mixture of carbonate of lime and clay; soft or indurated.

(See section on Rocks, p. 29.)

IV. **MAGNESIA.—Periclase.**—This earth is of extreme rarity in a pure state, being found only in minute crystals. It is found, however, in larger quantity, usually massive and foliated, as a hydrate in—

Brucite. White, greyish, or greenish. Fibrous; pearly, massive, and foliated. Forms veins in serpentine. Soluble in acids.

Magnesite is a carbonate of magnesia, crystallising in rhombohedral forms; cleavage perfect; of a white or light colour; hardness H = 3—4·5; Sp. Gr. = 2·8—3. At times fibrous, like asbestos, but differs in becoming brittle before the blowpipe. More slowly soluble in acids than calcite.

Magnesia forms the essential base in several silicates of common occurrence, already described.

In combination with carbonate of lime in definite proportions, carbonate of magnesia crystallises in rhombohedrons of white, yellow, and brown colours, translucent and of a pearly lustre, known as **Pearl Spar.** H = 3·8—4; Sp. Gr. = 2·8—2·9.

Composition.

Carbonate of Magnesia	45·6	$CaO{\cdot}CO^2 + MgO{\cdot}CO^2$.
Carbonate of Lime...	54·4	
	100·0	

It is more often granular and massive,—constituting extensive rock-masses, termed—

Dolomite, when pure. The term *Magnesian Limestone* is generally applied to the impure varieties, which contain an excess of carbonate of lime. Differs from calcite in not effervescing readily in cold dilute acid.

Meerschaum is a white, very light hydrous silicate of Magnesia.

Of the other earths two are of common occurrence, viz.:—

BARYTES, which occurs as a sulphate (*Heavy Spar*) (Fig. 10 *a*), and as a carbonate (*Witherite*). They are both distinguished by their weight, the Sp. Gr. of the former, which crystallises in tabular rhombic and rectangular prisms (Fig. 10 *a*), being 4·3—4·8; and of the latter, which crystallises in modified rhombic and in six-sided prisms, being 4·3—4·35. The sulphate is of frequent occurrence in mineral veins. Colour white or slightly tinged and vitreous; streak white.

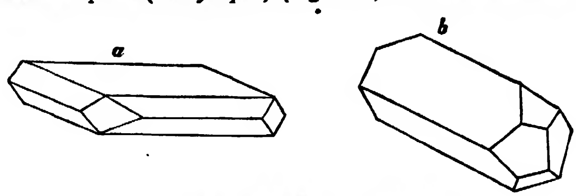


FIG. 10.—*a. Heavy Spar; b. Strontianite.*

STRONTIAN, which also occurs as a sulphate (*Celestine*), Sp. Gr. 3·9—4, and a carbonate (*Strontianite*), Sp. Gr. 3·6—3·72. The former crystallises in modified rhombic prisms (Fig. 9 *b*), sometimes flattened, often long and slender. Colour white or with a tinge of blue. It is a common mineral, in association with sulphur, in the lavas of Etna. It occurs also in Triassic strata. Strontian occurs in limestone, and is found with barytes and galena.

V. **SODA.**—This alkali is only found in combination with other substances.

As a nitrate, it occurs in some beds of late date in the rainless districts of South America.

As sulphate, carbonate, and borate (**Borax**), it occurs in some volcanic districts, and in dried-up lakes.

The metallic base of this alkali (sodium) combined with chlorine forms the chloride of sodium, or *Common Salt*, a substance largely dispersed in nature.

	Composition.	
Chlorine	60·7	Na Cl.
Sodium	39·3	
	100·0	

Crystallizes in cubes. H = 2; Sp. Gr. = 2·26—2. Soluble; decrepitates when heated.

Rock-salt forms beds, interstratified in various Tertiary and Secondary strata. In sea-water, chloride of sodium is present in the proportion of about 27 parts in 1000 parts by weight of water.

VI. **POTASH.**—This alkali, like soda, exists only combined, occurring as a nitrate in tufts or acicular crystals in some caverns, but more especially in the soil of certain hot parts of the globe, where it is the result of decomposition of organic substances in contact with alkaline and earthy bases in the soil.

It is, however, in combination with silica and alumina, forming the various silicates previously described, that soda and potash form such important elements in the rocks forming the crust of the earth.

VII. **CARBON.**—This abundant element occurs pure in the—

Diamond, forming the hardest of all known minerals. H = 10; Sp. Gr. = 3·53. Crystallises in octohedrons (Fig. 11 *a*) and dodecahedrons (Fig. 11 *b*). Limpid, and of various shades of yellow and black. Insoluble in acids; burns at a high temperature.

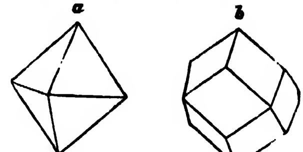


FIG. 11.—Diamond. *a. Octohedron; b. Dodecahedron.*

Graphite or **Plumbago.**—This is also a nearly pure carbon; amorphous, opaque black, with a metallic lustre; marks paper. H = 1—½; Sp. Gr. = 2—2.3. Insoluble.

Anthracite, *Coal, Jet, Lignite, and Amber*, consist of carbon with very variable proportions of oxygen and hydrogen. Nitrogen is sometimes present in very small quantities.

Bitumen, *Asphalte*, *Petroleum*, &c. consist of carbon in combination with variable proportions of hydrogen.

Carbon forms with oxygen carbonic acid-gas, which enters so largely (as much as 12 per cent. by weight) into the composition of limestone and all calcareous rocks.

VIII. **SULPHUR** occurs in a native state, sometimes in rhombic crystals, but more often massive. Its yellow colour, lightness, and ready combustion, render it easily recognisable. It is, however, more frequently found in combination with various metals, forming sulphides or sulphurets of those metals (see Table I. p. 9), which may be recognised by certain characters in common. Thus—

1. They generally have a highly metallic lustre.

2. Treated in powder with strong acids, they evolve sulphuretted hydrogen, easily recognised by its odour and by its blackening white lead.

3. Heated in an open tube, they disengage sulphurous acid, recognisable by its odour and by its turning litmus-paper red.

Sulphur also combines with oxygen and water to form sulphuric acid, which, united with many of the earths, forms minerals of common occurrence in nature.

The presence of sulphur, whether present as a sulphide or a sulphate, can be detected by fusing a fragment with carbonate of soda on charcoal in the blowpipe flame, and then placing a portion of the fused mass on a polished silver surface: a drop of water added to this will give a black stain to the metal.

IX. **CHLORINE.**—The only combinations of this element important to the geologist are those formed with sodium (common salt), just noticed, and potassium.

The only metals with which it is found naturally combined are silver and lead. Rendered soluble in the same way as the sulphates, the presence of chlorine is readily recognised by its forming a white precipitate on the addition of a few drops of a solution of nitrate of silver.

X. **IRON.**—This metal is most widely disseminated, though it has only been met with native in small grains (and doubtful masses) in basalt. Native iron, with a small proportion of nickel, is a common constituent of meteorites. It is, however, found chiefly in combination with oxygen and sulphur. With the former, it forms—

Magnetite, in which 72·4 parts of iron are combined with 27·6 parts of oxygen, forming a mineral consisting of the peroxide = 69, the protoxide = 31 parts. Crystallises in octohedrons and dodecahedrons (Fig. 11). Colour black; streak black. H = 5·5—6·5; Sp. Gr. = 4·9—5·2. This mineral is strongly magnetic. Composition $Fe^3 O^4$.

Oligiste or Specular Iron-Ore (Fig. 12 *a*).—Peroxide of iron. Colour steel-black, with a highly brilliant metallic lustre; streak red. H = 5·5—6·5; Sp. Gr. = 4·5—5·3. Crystallises in various modifications of a rhombohedron. Composition: iron = 70, oxygen = 30 parts ($Fe^2 O^3$). The earthy uncrystallised varieties of the mineral form,—

Red Hematite.—An amorphous peroxide of iron. It is usually massive, mammillated or fibrous, with external surface of very bright metallic lustre. Colour dark-red, approaching black; streak red.

Brown Hematite is the peroxide of iron combined with water, forming a hydrous peroxide. It is browner and blacker than red hematite, and is distinguished from it by having a brown streak. Its surface is often smoothly botryoidal or stalactitic. H = 5—5·5; Sp. Gr. = 3·6—4. The following are varieties more or less impure of this mineral:—

Limonite.—Massive or fibrous; dull; colour dark-brown to yellow.

Brown and Yellow Ochre.—Soft earthy varieties of limonite.

Pea-iron-ore, forming small dark-red or brown grains like an oolite or pisolite.

Bog-iron-ore.—An earthy, sometimes granular, blackish-brown hydrous variety of the last, formed in swampy ground.

The Protoxide of Iron does not occur native. In combination with carbonic acid it forms—

Chalybite, Spathose Iron, or **Siderite** (Fig. 12 *c*).—A mineral which crystallises in small rhombohedrons with curved faces, and is distinguished by its yellowish- or greyish-white colour and pearly lustre; streak colourless. Infusible; slowly soluble in acids. H = 3—4·5; Sp. Gr. = 3·7—3·85.

An earthy variety of this mineral, mixed with clay and marl, constitutes the common *clay ironstone* of the Coal-measures.

FIG. 12.—*a. Oligiste; b. Iron-Pyrites; c. Siderite.*

Iron is also found combined with sulphur, forming—

Magnetic Pyrites, which occurs massive or in hexagonal crystals of a bronze-yellow colour. H = 3·5—4·5; Sp. Gr. = 4·4—4·65. Composition: iron = 60·5; sulphur = 39·5; sulphuret or sulphide of iron; but the commoner combination, in which sulphur is present in larger proportion, is as a bisulphuret in—

Iron-Pyrites—a widely-dispersed mineral of a brass-yellow colour. H = 6—6·5; Sp. Gr. = 4·8—5·1. Striking fire with steel. It crystallises commonly in cubes (Fig. 12 *b*), the faces of which are often striated. Composition: iron = 47; sulphur = 53. It also crystallises in another system (rhombic), when, although there is no difference in its composition, its characters are nevertheless altered. It is then paler, and has the inconvenient property of decomposing readily on exposure to air and moisture. It is this variety that has fossilised the London-clay fruits and shells of Sheppey and of many other argillaceous formations, and which are consequently so difficult to preserve. It also forms the small balls, with a radiated structure, common in the Lower chalk. This variety is sometimes termed *White Iron-pyrites and Marcasite.*

Iron combines with phosphoric acid, forming—

Phosphate of Iror or **Vivianite,** which is, however, a rare mineral, except in peat-beds, where it is not uncommon as a blue earth or powder, formed by the decomposition of animal substances in presence of iron and vegetable matter.

Also with titanic acid, forming the grains of titaniferous iron common in many volcanic rocks, and as particles in some sands.

Iron is also the most common colouring ingredient of rocks and soils; various shades of yellow, red, green, brown, and black being due to iron in different states of oxidisation and hydration (see also p. 31).

There are two other substances which, although not occurring in such large quantities as the preceding, are still very widely dispersed, and are present in small quantities in most rocks. These are,—

1. **MANGANESE.**—This, next to iron, is the most common colouring ingredient of rocks, sands and gravels[1]. Its usual colour is black, but is also brown, reddish, and green, according

[1] It also forms the dendritic moss-like markings so common on the surfaces of joints and planes of bedding of some rocks.

(like iron) to its different states of oxidisation and combination. It occurs most commonly as a peroxide and as hydrous per- and sesqui-oxides (**Pyrolusite, Wad, Manganite**). The black oxide of manganese is distinguished from that of iron by having a black streak or powder, whereas that of Iron-oxide is red or yellow. The presence of manganese may also be detected by its producing with borax in the outer flame of the blowpipe a violet bead, which in the inner flame becomes colourless; also a manganese mineral fused on platinum wire with carbonate of soda imparts to it a fine greenish-blue colour, somewhat resembling turquoise.

2. **PHOSPHORUS.**—This element only exists in combination with oxygen, forming phosphoric acid, united to such bases as *lime, alumina, and iron*, to which reference has already been made (pp. 19, 23).

Phosphoric acid occurs commonly in many crystalline rocks. It has been found in a number of granites, syenites, serpentines, diorites, diabases, dolerites, basalts, &c., as well as in gneiss, in quantities varying from 0·17 to 1·24 per cent. This accounts for its frequent presence in so many sedimentary strata, derived from the decomposition and destruction of these older rocks. It explains also its common occurrence in soils and in many fossils.

3. **Fluorine** is, like phosphorus, dispersed in very small quantities in combination with other substances in many rocks, in some fossil bones and teeth, and in the soil.

The foregoing minerals embrace all those which enter commonly or as essential constituents into the composition of rocks. The others are of such rare occurrence, that, until the student has made further progress, and has occasion to specialise his work, they may be passed over. For reference the student can consult the works of Phillips, Miller, Dana, Descloiseaux, Dufrénoy, and other mineralogists.

CHAPTER III.

COMPOSITION AND CLASSIFICATION OF THE ROCKS.

Definition of 'Rock.' Rock-forming Minerals. Enumeration of (1) The Sedimentary Rocks: their Composition; (2) The Metamorphic Rocks; The Rocks of Igneous Origin; (3) The Volcanic Rocks; (4) The Plutonic Rocks. Variety of Rocks of Igneous Origin. Number of Rock Species. Use of the Microscope. Stratigraphical Divisions of the Rocks. Diagram-Table of the Great Groups into which the Sedimentary Strata are everywhere divided, and Map thereof.

Definition of Rock. The word 'rock' is used by the geologist to designate all those combinations of mineral matter, whether of the same sort or of several sorts, which are found in the crust of the earth in masses sufficiently large to be considered essential portions of that crust. Thus the term includes not only the hard and solid strata, but is applied also to the soft and incoherent beds of sand and clay interstratified with them.

It has been mentioned that the number of minerals is small compared with what it would be, were not the combinations of the elementary substances forming them restricted by rigid laws of definite equivalence and combining proportions. From the preponderance of a few and the exclusion of so many of these minerals the varieties of rock are far less numerous than might be supposed [1]; for of the some 600 known minerals, not more than about thirty enter as essential constituents into the composition of rocks; and even of these thirty, only a third play an important part: the others occur as accessory, either of occasional occurrence, or else in small quantities in certain rocks, or lining fissures, and in mineral veins, cavities, geodes, &c.

Unlike minerals, in which the proportions of the constituent parts are definite and fixed, in rocks the component parts are indefinite and mixed in variable proportions. Therefore, the varieties are in reality almost infinite, and the limits of rock-species often extremely difficult to define. The number is consequently variously estimated by different petrologists at from 200 to 300 [2].

[1] See Cotta's 'Rocks classified and described;' Rutley's 'The Study of Rocks;' and Chas. D'Orbigny's 'Description des Roches.'

[2] Omitting varieties, the rocks in M. Daubrée's Classification of the Collection in the Museum of Natural History at Paris are comprised under 104 species.

Rock-forming Minerals. The attempt to define the proportion of the more important minerals in the earth's crust, although it can only be distantly approximate, serves at all events to show their relative geological abundance and value. On the assumption that the solid crust of the earth consists, on the average, of a thickness of three miles of sedimentary strata, and fifty-seven miles of crystalline and igneous rocks, it has been estimated[1] that, taken together, the relative proportion of the ten most abundant minerals is in this mass about as follows:—

1.	Felspar	48 parts.
2.	Quartz	35 "
3.	Mica	8 "
4.	Talc	5 "
5.	The Carbonates of Lime and Magnesia	1 "
6.	Amphibole (Hornblende)	
7.	Pyroxene (Augite)	
8.	Diallage	1 "
9.	Peridot (Olivine)	
10.	Clay (in all its forms)	1 "
11.	Other substances	1 "
		100 "

The other constituent minerals are garnet, epidote, leucite, tourmaline, andalusite, the various oxides of iron, carbonate of iron, titanite of iron, iron-pyrites, oxide of manganese, sulphate and phosphate of lime, fluor-spar, chloride of sodium, sulphur, and the various coals, lignites, and bitumens.

Enumeration of the Sedimentary Rocks. Rocks are divided into, 1st. Sedimentary or Stratified rocks, and 2nd. Unstratified and Intrusive. The former are composed of argillaceous, calcareous, and siliceous substances, separate and variously intermixed.

The Argillaceous Strata consist essentially of—

1. **Clays.**—Which are soft hydrated silicates of alumina with more or less free silica; insoluble in acids. They have the property of becoming plastic with water and hardening in fire. They usually contain diffused oxide or sulphide of iron, or some organic carbonaceous matter, which gives them a dark bluish-grey colour. They are, however, often coloured red, purple, yellow, and green by the peroxide and protoxide of iron. Some clays are slightly calcareous, and contain segregated masses of impure carbonate of lime called septaria, and crystals of sulphate of lime (selenite). Example: *The London Clay; the Reading or Mottled Clays; the Oxford Clay, &c.*

According as the clays are mixed with other substances they constitute,—

2. **Fuller's Earth.**—When a clay contains such an excess of silica, as, instead of being plastic, to fall to a fine powder in water, it is termed 'Fuller's earth.' *Locality, Nutfield.*

[1] C. D'Orbigny, Op. cit., p. 2.

3. **Loam.**—Clay mixed with a certain proportion of fine sand. It is usually grey or light-brown in colour owing to the presence of a small quantity of the peroxide of iron. Ex. *The upper part of the London Clay; some of the Woolwich and Reading beds; brick-earths.*

4. **Shale.**—Clay and marl more or less indurated and laminated in the plane of original deposition—a condition promoted by the presence of accidental minerals such as mica, sand, and carbonaceous or bituminous matter; they are known as micaceous and carbonaceous shales. Ex. *Coal-Measures Shale; Kimmeridge-Clay Shale.*

5. **Marl.**—Clay containing a certain considerable proportion of calcareous matter. When the clay retains its soft plastic character, it is termed '*Marl*'; when, on the other hand, it is indurated, it is called '*Marlstone*,'—a rock which disintegrates and falls to pieces on exposure to the weather. With an increase in the proportion of the lime it passes into argillaceous limestone, and then into pure limestone. The proportion of carbonate of lime is indicated by the greater or less solubility in dilute hydrochloric acid. It is often mixed with sand, mica, bitumen, or oxide of iron. Ex. *The Chalk-Marl; the Marlstone of the Lias.*

The composition of these argillaceous strata is extremely variable. The following are some of different geological periods:—

	EOCENE.	CRETACEOUS.	JURASSIC.	CARBONIFEROUS.		SILURIAN.
	Light col^d. Pottery Clay, Poole. (*Percy.*)	Fuller's Earth, Nutfield. (*Berthier.*)	Blue Clay (Kimmeridge or Oxford), Wiltshire. (*Riley.*)	Fire-clay, Stourbridge. (*Wills.*)	Red Tile-clay, Broseley. (*Maw.*)	White Saponaceous Clay, Horderley. (*Maw.*)
Silica	48·99	57·0	55·16	73·82	64·06	45·48
Alumina	32·11	10·3	21·88	15·88	20·60	23·52
Lime	0·43	...	sulph. 2·62	traces	0·12	carb. 11·10
Magnesia	0·22	3·0	1·51	"	0·04	1·44
Potash	3·31	...	2·22	0·90 (Potash and Soda)	0·91	2·15
Soda	...	...	2·40		0·44	0·54
Protoxide of Iron ...	2·34 (Protoxide and Peroxide)	6·7	4·17	2·95	0·32	1·76
Peroxide " ...	...		...	...	6·84	...
Protox. of Manganese	...	...	...	...	0·09	0·07
Titanic Acid	...	...	2·19	...	0·62	...
Water	11·99	23·0	7·25	6·45	5·85	13·88
	99·39	100·0	99·40	100·00	99·89	99·94

	CHALK-MARL. Farnham. (*Paine and Way.*)	CHLORITIC CHALK. Cambrai. (*Savoye.*)	KIMMERIDGE. Clay-marl, Dorset. (*Maw.*)	JURASSIC. Jura. (*Mène.*)	KEUPER-MARL. Worcester. (*Voelcker.*)	KEUPER-MARL. Tübingen. (*Gmelin.*)
Silica and Clay... ...	26·05	40·965	65·72 (Silica, Clay, Alumina and Iron-oxide)	40·2	53·62	59·12
Alumina and Iron-oxide	3·04	2·200		3·8	25·38	7·32
Carbonate of Lime ...	66·67	56·426	34·28	52·5	7·69	14·56
Carbonate of Magnesia	0·68	0·204	...	1·2 *a*	5·10	19·10
Phosphoric Acid ...	1·82	0·205	...	...	2·91 *b*	... ...
	98·26	100·000	100·00	96·17	94·70	100·10

a Sulphate of lime. *b* Alkalies and loss.

The varied colouring of clays (and other rocks) is due to the presence of iron in various states of oxidisation, and to organic matter. The latter colours the clay from light-grey to black. The former, in the state of anhydrous peroxide, imparts the deep reds which, on becoming hydrated, change to bright yellow, while intermediate conditions and concentration of the iron give shades of brown and purple. The grey clays so largely developed as clunches and fire-clays in the coal-measures owe their colour, in addition to the presence of carbonaceous matter, to carbonate of the protoxide of iron in a fine state of subdivision, and occasionally to the presence of finely divided bisulphide of iron[1], as in the following cases cited by Mr. Maw :—

	London Clay, Bawdrey Cliff. *Voelcker.*	Kimmeridge Clay, Wilts. *Voelcker.*	Oxford Clay, Wilts. *Voelcker.*
Protoxide of Iron (carb.)	1·68 per cent.	·08 per cent.	1·12 per cent.
Peroxide "	... ...	4·32 "	3·25 "
Bisulphide "	1·031 "	1·42 "	1·10 "
Carbonate of Lime ...	... ...	4·28 "	... ...
Sulphate "	... ...	5·35 "	1·3 "

The iron protoxide in the London Clay sometimes contains traces of the basic sulphate of iron—a comparatively colourless salt resulting probably from decomposition of the bisulphide.

In the white and light grey clays, iron occurs principally in the form of carbonate of the protoxide.

It has also been shown that many clays contain a notable proportion of titanic acid. It is found in some Coal-measure fire-clays, and in the London Clay, sometimes exceeding 1 per cent.; also in even larger quantity in a blue clay (Oxford or Kimmeridge?) from Wiltshire, and traces of it occur in a clay from Ewell (Woolwich and Reading series?)[2]. Forchhammer also found titanic acid in a clay from the Faroe Islands.

Calcareous Strata. These are of various degrees of hardness, colour, and composition, some being soft and earthy, others solid and compact.

1. **Limestones** when pure consist almost entirely of carbonate of lime. They are hard and dense, sometimes crystalline, and their specific gravity varies from 2·6 to 2·7.

They are more frequently impure and coloured by iron and organic matter. The fissures in them are often lined with crystals of calcite, and in some limestones there are layers of dark chert or flint. Ex. *Derbyshire Limestone; Clifton Rocks; Plymouth Limestone.*

[1] The student should consult the interesting and beautifully illustrated paper on the subject of the colouring of rocks by Mr. George Maw in the 'Quart. Journ. Geol. Soc.' for Nov. 1868, p. 351; and also his 'Catalogue Specimens of Clays in Museum of Practical Geology,' 1871.

[2] E. Riley, 'Journ. Chem. Soc.,' vol. xv. p. 311.

2. **Oolite.**—Calcareous freestones in which the carbonate of lime exists in the form of rounded grains, like the roe of fish, or peas, embedded in a more or less pure calcareous matrix. They form rocks which are generally light-coloured, and cut freely and easily, Sp. gr. 1·9 to 2·3. Crystals and veins of calcite are common in cavities and cracks. Portland Oolite contains layers of dark chert, like flints in chalk. Ex. *Bath Stone; Portland Stone; Caen Stone.*

3. **Chalk.**—An earthy, nearly pure carbonate of lime, forming a soft white rock, soiling the fingers. The lower beds of the Chalk contain, however, various and often large proportions of alumina and silica. It contains, as segregated minerals, flint, chalcedony, and iron-pyrites; and as adventitious minerals,—glauconite, quartz grains, etc. Ex. *The Chalk of Kent and Sussex.*

4. **Lithographic Stone.**—An extremely fine-grained compact light-yellow stone, containing a very small percentage of silica and alumina. It is, like chalk, an almost pure carbonate of lime. *Loc.: Solenhofen.*

5. **Dolomite; Magnesian Limestone.** Pure dolomite forms a light-coloured rock, consisting of a definite combination of 54 parts of carbonate of lime, and 46 parts of carbonate of magnesia, but many limestones contain variable proportions of carbonate of magnesia, and these are usually termed magnesian limestones. They are often difficult to distinguish from ordinary limestones. On the whole, they are harder, and of greater specific gravity; dissolve very slowly instead of rapidly in dilute acids; are often gritty to the touch; and, when more crystalline, they have a granular and pearly lustre. Crystals of bitter-spar and calcite are met with in cavities of the rock; and such foreign ingredients as quartzose sand and mica are also often present. Ex. *The Magnesian Limestone of Sunderland; the Dolomitic Limestone of the Muschelkalk; the Dolomite Mountains of the Tyrol.*

6. **Hydraulic Limestone.**—A limestone into the composition of which silica and alumina and sometimes magnesia enter, in the proportion of from 20 to 35 per cent., giving a lime that has the property of setting under water. Ex. *Some of the Lias limestones; the Septaria of the London and Kimmeridge Clays.*

7. **Siliceous Limestone.**—A limestone intimately mixed with silica (soluble). It is very hard and usually light-coloured, and the fossils in it are often replaced by chalcedony. *Loc.: Common in amongst some of the Tertiary Strata of France; some beds of the Mountain Limestone of Northumberland.*

8. **Calcareous Tufa: Travertine.** A white or semi-crystalline, porous, subaerial deposit of carbonate of lime, formed by springs. Ex. *Matlock; Tivoli; Clermont.*

The following are the analyses of some of the principal types of calcareous rocks:—

	CHALK WITH FLINTS. Shoreham, Kent. (*D. Forbes.*)	SHELLY LIMESTONE. (Portland), Chilmark. (*Com. Report.*[1])	HYDRAULIC LIMESTONE. Kimmeridge. (*Com. Report.*)	GREAT OOLITE. Bath. (*Com. Report.*)	MAGNESIAN LIMESTONE. Bolsover. (*Com. Report.*)
Carbonate of Lime	98·40	79·0	75·7	94·59	51·1
" Magnesia	0·08	3·7	... ...	2·50	40·2
Silica	1·10	10·4	15·0	... ...	3·6
Iron and Alumina ...	0·42	2·0	8·2	1·20	1·8
Water and loss ...	... ...	4·2	1·1	1·71	3·3
	100·00	99·3	100·0	100·00	100·0

[1] Report of Commission on the Building Stones for the Houses of Parliament, 1831.

	LITHOGRAPHIC LIMESTONE. Solenhofen. (*Gmelin*)	JURASSIC LIMESTONE. Geneva. (*Kosmann.*)	DEVONIAN. Marble. (*Pagnoul.*)	DEVONIAN. Dolomite. (*Pagnoul.*)	SILURIAN LIMESTONE. (*Lambert.*)
Carbonate of Lime	96·24	91·52	94·0	57·8	44·6
„ Magnesia	0·21	1·71	0·8	39·7	3·6
Silica ... ... }	2·02	}	3·3	0·6	51·4
Iron and Alumina }		} 1·58	1·9	1·9	... ...
Phosphate of Lime	... ..	1·41	trace	... ...	... ...
Alkaline Carbonates	... ...	3·77	... ...	... ...	loss 0·4
	98·47	99·99	100·0	100·0	100·0

Quartzose Strata. The base of these strata consists of siliceous matter, generally in the form of fine grains of quartz. When these are uncemented and incoherent they form—

a. **Sand-beds**—loose aggregates of grains of quartz, often with minute plates of mica, sometimes with green grains of glauconite: frequently slightly coloured by the iron and manganese peroxides. Ex. *The Bagshot Sands; the Thanet Sands; the Sands of Reigate and Hindhead.*

When, on the other hand, they have been cemented and indurated, they form—

b. **Sandstones**—consisting of grains of quartzose sand, generally colourless, bound together by siliceous, argillaceous, calcareous, or ferruginous cements, forming easily-worked freestones or hard ragstones, and passing into indurated quartzites. They frequently also contain mica and felspar. They vary in colour from white, yellow, grey, brown, red, and purple, to black,—the colour being due, as in the case just mentioned of the clays and limestones, to iron in various stages of oxidisation and hydration, to manganese, and to carbonaceous matter.

They (*b*) may be divided into,—

1. **Ordinary Sandstones.**—Which are formed of small grains of quartz, more or less rolled, and have a cement of silica with little admixture of clay. Their colour varies with the nature of the cementing material. They are generally soft, often friable, and permeable to water. When, however, the cement is siliceous, they pass into hard impermeable saccharoid sandstones and quartzites. Ex. *The Coal-Measure Sandstones; some Sandstones of the New Red; the Lower-Tertiary Sandstones (Druid Sandstone).*

2. **Calcareous Sandstone** (Macigno, Ital. Geol.). A common more or less compact form in which the quartzose grains are cemented together by carbonate of lime. Ex. *Kentish Rag, Maidstone; Nummulitic Strata of Switzerland and North Italy.*

3. **Felspathic Sandstone** (**Arkose,** Brongniart).—A sandstone in which is interspersed grains of felspar, sometimes decomposed. Ex. *Common in the Millstone-grit and Permian strata, and many sandstones near granitic centres.*

4. **Argillaceous Sandstones** (**Psammite,** Hauy; **Metaxite,** Cardier).—Sandstones of which the grains are mixed in larger proportions with clay, often coloured by iron oxides. Ex. *Some Coal-Measure Sandstones; 'New Red' Sandstones.*

5. **Flagstones** (**Psammite schistoïde,** Brongn.)—Hard sandstones which, owing to the presence of mica or other substances, split in laminæ parallel with the planes of deposition. Ex. *Yorkshire Flagstones; Llandeilo Flags.*

6. **Marly Sandstones** (**Molasse**).—Calcareous sandstones, often micaceous, and generally grey

or yellowish grey. When the cement consists of a calcareous marl in large proportion, it forms a soft and friable rock. Ex. *Miocene Strata of Switzerland, Tuscany, Vienna.*

7. **Sandstone-Grit.**—A sandstone in which the grains of quartz are larger than usual, or in which there is an admixture of small pebbles. Ex. *Portions of the Millstone-Grit.*

8. **Green Sandstone.**—So called owing to the presence of grains of dark-green glauconite. Ex. *Some of the Strata of the Upper Greensand; Isle of Wight, Eastbourne, Godstone.*

A curious variety of sandstone was noticed a few years since in the Jurassic series of France, and received the local name of—

9. **Gaize.**—The matrix is a soluble silica [1], which has been precipitated in the state of an impalpable white powder of small specific gravity. It forms an important constituent of some strata, and is particularly abundant in the Upper Greensand of both England and France, being present in some beds to the extent of 40 to 70 per cent. Ex. *Upper Greensand of Farnham and Merstham (firestone); Oxfordian beds of the Ardennes.*

10. **Ferruginous Sandstone.**—A sandstone with a cement of the hydrated peroxide of iron, which gives the rock a yellow or brown colour. Ex. *Some of the Wealden, and of the Lower Greensand Strata; the Carstone of Cambridge and Lincolnshire.*

11. **Mudstone.**—A soft, fine-grained, argillaceous sandstone, in which the proportion of clay is so large that it softens and falls easily away on exposure to the weather. Ex. *Some of the Ludlow and Wenlock Strata.*

The following is the composition of a few of these Sandstones:—

	RED SANDSTONE. (Bunter), Shiffnall. (*Maw.*)	PURPLE SANDSTONE. (Caradoc), Horderley. (*Maw.*)	LIGHT-COLD. CARBONIFEROUS SANDSTONE. Heddon. (*Com. Report.*)	MAGNESIAN SANDSTONE. (Permian), Mansfield. (*Com. Report.*)	CALCAREOUS SANDSTONE. Molasse (Miocene) Aix-les-Bains.
Silica [2]	96·31	92·49	95·1	49·4	71·45
Alumina	0·80	2·47	Al. and Fe. 2·3	Al. and Fe. 3·2	0·25
Carbonate of Lime	0·35	... ...	0·8	26·5	25·15
„ Magnesia	0·75	... ...	... ...	16·1	2·50
Iron-peroxide	1·30	3·51	... ...	... ...	0·85
„ protoxide ...	... ...	1·11	... ..	... ...	
Combined water ...	0·65	0·42	1·8	4·8	... ...
	100·16	100·00	100·0	100·0	100·20

Greywacke. An old and not inconvenient, though somewhat ill-defined term applied to fine-grained and coarse-grained composite dark rocks consisting of a body of quartz grains with a cement of slaty matter, occasionally slightly micaceous and calcareous. It often closely approaches a state of metamorphism. *Loc. Common amongst the older palæozoic rocks.*

The red colouring of the Triassic, Permian, Devonian, and other rocks, and the purple of some sandstones, is owing, as in the case of the clays, to the presence of from 4 to 15 per cent. of the anhydrous peroxide

[1] Called 'Soluble Silica' from its being soluble in a boiling solution of potash.

[2] In these, and with few exceptions in all other sandstone analyses, the distinction between the silica present in the form of quartz grains, and that present as an amorphous powder or in combination, is not shown. In most sandstone rocks, however, the 'silica' usually represents the grains of quartz.

of iron; and the dull brown and bright yellow, to the hydrous peroxide. The blotching and variegation of the beds are due to the hydration and de-oxidisation of the peroxide of iron by organic matter, and the removal, in some cases, of the iron by carbonated waters. Sometimes the iron is present as a green silicate. In some sandstones black fields of colour are due to the presence of the peroxide of manganese [1].

The Sandstones and other sedimentary strata, consisting of beds formed by fragments of the rocks of one age imbedded in a paste or matrix of finer materials at some subsequent period, have been grouped under the general term of *clastic rocks*. They also comprise—

1. **Breccias.**—Strata formed of fragments, always more or less *angular*, of any rocks, imbedded in a compact calcareous, argillaceous, siliceous, or ferruginous base or cement. Ex. *The breccia of the Permian Series; some Marbles.*

2. **Conglomerates.**—In these the fragments have been worn round, and reduced to pebbles—sometimes of large size. The matrix may be calcareous, argillaceous, siliceous, or ferruginous. Some varieties are called puddingstones. Ex. *The Conglomerates of the Old Red and New Red Sandstones; the Puddingstones* (*Lower Tertiary*) *of Hertfordshire.*

Such detrital beds may be of any age. We have, further, those of more recent date, which are superficial. They consist of—

1. **Loess or Brick-earth.**—A light-brown or reddish loam, sometimes calcareous and containing small calcareous concretions called 'race.' Ex. *The Brick-earths of the Lower Thames and Medway Valleys; the Loess of the Rhine.*

2. **Gravel.**—A loose accumulation of fragments, more or less angular, or sub-angular and rounded, derived generally from the rocks of the district or the same hydrographical basin, imbedded in a matrix composed of the finer and softer débris of the same and associated strata. Ex. *The flint* (chalk-derived) *gravel of the neighbourhood of London; the oolitic* (from the Oolitic strata) *gravel of the neighbourhood of Oxford.*

3. **Shingle.**—The more rolled and rounded rock-fragments formed on shores and shoals. It has usually a matrix of quartzose sand. Ex. *The recent Coast-beaches; the Tertiary Pebble-beds of Blackheath and Addington.*

The foregoing are the principal rocks of the sedimentary strata and superficial drift-beds, i.e. those strata which have been deposited, as their name implies, as sediments in former seas, estuaries, lakes, or rivers. Originally in the state of loose sands, silts, and shingle, they have since been indurated by pressure, heat, and the infiltration of cementing bases, such as carbonate of lime, soluble silica, the oxides of iron, etc. When the heat and pressure have been sufficiently great, and have been aided by favourable conditions of moisture, these rocks have undergone further and more radical changes. They are then known as—

Metamorphic Rocks [2], in which the molecular structure has been

[1] See Maw, *op. cit.*, p. 398.

[2] There is much difference of opinion as to where the line between these and the unaltered rocks should be drawn. Some geologists would exclude the ordinary slates.

altered, new chemical combinations formed, and the structure rendered more or less crystalline. So great is this change in some cases that the line of demarcation between rocks of metamorphic and those of igneous origin is often extremely difficult to determine. Rocks formerly supposed to be of igneous origin are now commonly considered to be altered sedimentary strata; by many, granites are now held to be due to changes of this character. Calcareous and quartzose strata are less changed in general appearance than those of argillaceous origin. The following are the most common metamorphic rocks:—

Crystalline Limestone.—Statuary marble (**Protocalcite**, Cordier). These are ordinary limestones that have been rendered more or less granular and crystalline by heat. The colour, if due to mineral matter, is retained and even heightened and varied; but, if due to organic matter, it is destroyed by the heat, and the result is a white statuary marble. Ex *Carrara* (*Triassic*) *Marble*; *Sienna Marble*; *Donegal Marble*.

Cipoline.—A crystalline limestone with veins and streaks of talc, commonly associated with talc-schists. Loc. *The Alps*; *the Pyrenees*; *Corsica*.

Micalcite (Cordier).—Another less common variety of crystalline limestone, in which mica takes the place of talc. In both these varieties the foreign ingredient is only in the proportion of about 5 to 10 per cent.

Dolomite.—A white or light yellow crystalline or saccharoid rock consisting of carbonates of lime and of magnesia in definite proportions (p. 20). Loc. *The Alps*; *the Tyrol*; *the Pyrenees*.

Quartzite is an altered and hardened sandstone, usually grey, yellow, or red, in which the grains of quartz have more or less run together, producing a glistening fracture and a very hard texture. Loc. *Lickey Hill* (Warwickshire); *some Devonian rocks* (Devon).

Clay-slate (Phyllade).—Dark-blue, purple, and green[1] rocks, compact and fine-grained, and consisting of an argillaceous base, with, at times, mica, and, according to C. D'Orbig .y, talc in a state of extremely fine division. By some petrologists it is looked upon as a silicate of alumina and the alkalies. It cleaves into thin laminæ at various angles to the plane of bedding, forming *roofing* and *drawing slates*. Crystals of iron-pyrites are often abundant. Ex. A common condition with many of *the older Palæozoic rocks*.

[1] Mr. Maw considers the colours of the Welsh slates to be a combined result of original sedimentation and of secondary causes: the dark olive-green and blue being of structural origin, and the light-green and blotching being due to subsequent removal and bleaching of the colouring ingredients.

Thus, *the Blue Slate of Llanberis* contains . . . . and *the bleached bands* in the slate

Peroxide of Iron	... 5·68	... ...	1·59 per cent.
Protoxide of Iron	... 0·48	... ...	0·22 „

In other cases the colour is due to the conversion of the peroxide of iron into protoxide, as in the Penrhyn slates:—

	Purple Slate.		*Green Slate.*
Peroxide of Iron	6·540	... ...	0·00
Protoxide „	0·874	... ...	5·49
Sulphur	0·031	Iron bisul.	0·15

The darker colours of slate are also sometimes due to the presence of carbonaceous matter, and, according to C. D'Orbigny, of graphite in a state of fine division.

The composition of some of these metamorphosed rocks is as under:—

	CRYSTALLINE LIMESTONE. Carrara. (*Berthier.*)	CRYSTALLINE LIMESTONE. Tiree. (*Boué.*)	DOLOMITE. Italian Alps. —	QUARTZITE. — (*Berthier.*)
Silica	...	...	...	97·75
Carbonate of Lime	98·1	94·94	53·4	...
" Magnesia	0·9	1·13	44·2	...
" Manganese	1·0	3·19	2·4	...
Alumina and Iron	...	0·54	...	0·50
Water	...	...	...	1·00
Loss	...	...	...	0·75
	100·0	99·80	100·0	100·00

The limestones and dolomites often contain many accessory minerals; amongst them are garnets, apatite, pyrites, graphite, &c. The Tiree limestone contains crystals of augite.

Schistose Rocks: originally sedimentary beds of variable composition, the ingredients of which have, by a process of metamorphism, entered in new combinations, giving rise to various silicates, and developing a laminated arrangement of the constituent parts known as '*foliation*.'

There are many varieties of these rocks, of which the chief are—

Mica-Schist.—Slaty rocks consisting essentially of quartz and mica, the latter often in large proportion, which gives them a glossy and silvery surface; but the fine cleavage of the clay-slate is wanting. The fissile character in this and the other schists is due to foliation. Garnets are of common occurrence in this rock. Loc. *Cornwall; Devon; Wales; Aberdeenshire; Inverness-shire; Donegal.*

Hornblende Schist (Amphibolite).—A massive dark-coloured hornblendic rock with or without quartz. It is a more flaggy and tougher rock than the preceding. Crystals of magnetite are of not unfrequent occurrence. Loc. *Cornwall; Inverness-shire; Donegal.*

Talc-Schist.—Talc with small, but variable, proportions of quartz and felspar. It is greasy or soapy to the touch, and of light-greenish or greyish colour. Loc. *North Wales; Loch Fyne.*

Chlorite-Schist.—Same rock as last, but of a darker green colour, owing to the presence of chlorite. It is often rich in accessory minerals. Loc. *North Wales; Cornwall; Inverness-shire.*

Calc-Schist.—Another of this group of schistose rocks in which calcite is the extraneous element.

Gneiss.—Consists, like granite, of quartz, felspar, and mica in variable proportions; always, however, exhibiting a more or less foliated structure, in which respect it differs from granite, though they frequently appear to pass into one another. Gneiss also passes into mica-schist. It varies, like granite, in colour and in composition, being sometimes hornblendic. In places mica largely predominates, when the rock becomes more fissile and dark. At other times it is lighter coloured, and more banded, owing to the preponderance of quartz. Loc. *Anglesea; Ross-shire; Inverness-shire; Donegal; Wicklow.*

These metamorphic rocks are often rich in accessory minerals. Their

ultimate chemical composition varies with the constituent minerals. The following analyses give an approximate average:—

	ROOFING-SLATE. Wales. (*Haughton.*)	ROOFING-SLATE. Camelford. (*J. A. Phillips.*)	MICA-SCHIST. Pyrenees. (*Fuchs.*)	CHLORITE-SCHIST. Hartz. (*Fuchs.*)	KILLAS[1]. (SLATE). Cornwall. (*J. A. Phillips.*)	GNEISS. Hartz. (*Fuchs.*)
Silica	60·50	58·35	71·26	33·72	50·80	65·22
Alumina ...	19·70	22·04	20·03	19·81	20·90	16·35
Lime	1·12	0·39	0·28	0·60	1·56	3·27
Magnesia ...	2·20	1·10	trace	12·01	trace	2·06
Potash... ...	3·18	2·45	2·48	trace	0·91	2·74
Soda	2·20	1·23	0·59		4·20	8·03
Iron-protoxide	7·83	2·57	3·61	24·83	5·14	1·00
„ peroxide	...	6·96	1·10	...	13·39	...
Titanic acid	...	0·23	...	...	trace	...
Water	3·30	4·60	1·63	9·27	3·20	2·25
	100·03	99·92	100·98	100·24	100·10	100·92

Amongst the class of rocks often intrusive, there are varieties which are considered to be more distinctly of metamorphic origin, as some—

Serpentines Var.—A metamorphic calcareous form of Serpentinous rock called *Ophicalcite*. Ex. *Some Cambrian rocks of Anglesea; the green marble* (*so-called*) *of Connemara.*

Granites.—The granite of Donegal is considered by Haughton to be of metamorphic origin.

Syenites.—The syenite of the Malvern Hills is held by Holl to be a metamorphic rock.

The question of the metamorphic origin of this class of rocks will be a subject of discussion in the chapters on Metamorphism (xxiii. and xxiv.).

IGNEOUS ROCKS.

These are the rocks underlying the sedimentary strata, and which have been protruded into or ejected through them in a state of fusion. They consist of amorphous, crystalline, and vitreous masses, mostly without stratification, and are commonly divided[2] into—

1. **Volcanic Rocks**—or such as have been ejected or have welled out on the surface, and have therefore cooled and consolidated rapidly. These rocks are generally amorphous, in places vesicular, sometimes columnar, and often interstratified with other rocks.

2. **Plutonic Rocks**—or such as have been formed under conditions of depth and pressure, and have cooled slowly, thereby receiving a more or less distinct crystallisation of the component minerals.

The igneous rocks are further divided litho-chemically into those in which silica predominates, and which, from this substance acting as a weak acid, are termed *acidic rocks* (granites, trachytes, etc.), and those with less silica, called *basic rocks*, from the earthy bases and metallic oxides being in excess (basalt, diorite, etc.).

[1] This specimen was taken at the depth of 100 fathoms.

[2] This division will be somewhat modified in the chapters on the origin of these rocks. I here follow the ordinary grouping.

1. *Volcanic Rocks.*

These again may be grouped into those in which augite or pyroxene predominate (forming the most numerous class), and those in which felspar and silica are in larger proportion.

a. *Augitic or Pyroxenic Group.*

Lava—is the molten matter erupted in streams from volcanoes, and which has cooled and consolidated under sub-aërial conditions. All lavas possess certain characters in common, such as an amorphous, and sometimes vitreous, structure; scoriaceous or vesicular near the surface, owing to the escape of vapour or gases, but becoming compact and solid beneath. In the older scoriaceous lavas the vesicular cavities have often become filled with siliceous, zeolitic, or calcareous minerals; and then the rock is termed amygdaloidal. Lavas are generally, but not invariably, dark-coloured; the colour varying according to the predominant base. The following are the more common varieties:—

1. **Dolerite.**—An intimate, dark-grey, or black compound of augite and labradorite, and some titaniferous iron, in which the separate minerals can rarely be distinguished. The ordinary lava of volcanoes. Ex. *The lavas of Etna, Iceland, Auvergne, &c.*

2. **Leucite-lava** (**Amphigenite**, Cordier).—In this lava the labradorite, generally the main constituent of lava, is replaced in part or wholly by leucite; the characteristic trapezohedral crystals of the latter being often disseminated in the mass (*Leucitophyre*, Brongniart). Ex. *Many of the lavas of Vesuvius.*

3. **Basalt.**—There is little or no distinction in mineral composition between dolerite and basalt, except that the latter more frequently contains grains or crystals of olivine, has a roughly conchoidal fracture, and is generally more massive, homogeneous, and blacker, and is more often columnar. They pass one into the other. Loc. *The Giant's Causeway; Staffa; Auvergne.*

'*Gallinace*' is a term which has been used by Cordier to denote the more vitreous varieties of basalt. These are also known under the names *Hyalomelane* and *Tachylite*.

Trap is a term which has been applied to designate lavas of somewhat uncertain characters, and more especially to those dark compact greenstones or basalts, of which the successive streams have flowed in great horizontal sheets and have given rise to a step-like structure, as in the case of the lavas of the Faroe Islands, the Deccan, Norway, &c. I have explained the reason for this further on. (See Chapter xxi.)

b. *The Felspathic Group.*

The rocks of this group differ from ordinary lavas by their generally lighter colour—sometimes nearly white; by a frequent granular and often a porphyritic texture, and by being rarely scoriaceous or vesicular. They contain also more silica and less lime. At the same time there are modifications in both groups that show transitional varieties.

1. **Trachyte.**—So called from its roughness to the touch—a distinguishing feature of this class of rocks. It consists of a granular glassy felspar (sanidine) and oligoclase, with hornblende or augite, grains of quartz and mica (variety *Biotite*), and separate crystals of oligoclase. There are many varieties. Loc. *Drachenfels; Mont Dore.* An earthy variety adhering strongly to the tongue is termed Domite (Puy de Dôme).

The other species are—

2. **Rhyolite.**—Brightly vitreous allied to trachyte[1], but containing more free quartz in grains, and generally less hornblende and mica. Colours various. It passes into 'Perlite.' Loc. *Hungary; New Zealand; Colorado.*

3. **Obsidian.**—A translucent volcanic glass; usual tints smoky and black; generally found associated with the more acidic lavas. Loc. *Mexico; Iceland; Teneriffe.*

4. **Phonolite** (Clinkstone).—A compact, dark-greenish or brownish, felspathic rock, of uncertain composition, often slaty in structure or breaking into tabular masses, sonorous under the hammer. Weathers white. There are many varieties Loc. *Scotland; Mont Dore.*

5. **Pumice** is a very vesicular or spongy, silvery-white condition of some of the more fusible acidic lavas. It is so light as to float on water. Loc. *Lipari Islands; Teneriffe; Pacific Islands; Guatemala.*

6. **Andesites** consist of a plagioclase felspar, with hornblende, augite, quartz, and generally some magnetite. They are divided into hornblende-andesite and augite-andesite, both either with or without quartz. One variety is termed **Dacite**. Loc. *The Rocky Mountains; Transylvania.*

7. **Propylite** is a rock allied to the andesites and to the trachytes. It consists of felspar intimately mixed with hornblende, with or without quartz. Loc. *The Rocky Mountains; Transylvania.*

8. **Volcanic Ash.**—A term applied to rocks presumed to be formed of the sub-aërially discharged cinders and ashes of any of the foregoing varieties of volcanic rocks. Having been interstratified with sedimentary strata, they have become solidified, and often metamorphosed. Loc. *Beds interstratified with the Silurian strata of Wales and Cumberland.*

The following analyses of these volcanic rocks will serve as examples of their ordinary chemical composition.

		Silica.	Alumina.	Lime.	Magnesia.	Potash.	Soda.	Iron-protoxide.	Iron-peroxide.	Manganese-protoxide.	Water and other Substances.	Titanic Acid, Ti.; Fluorine Fl.; Phosphori Acid, Ph.; Chlorine, Cl.; Zinc, Zi.; Carbonic Acid, CO.	Total.
Rhyolite, Hungary ..	*a.*	75·22	13·22	0·75	0·34	6·00	1·72	2·46	..	..	3·27	—	102·98
Obsidian, Mexico ..	*b.*	78·0	10·0	1·0	—	6·0	—	—	2·0	1·6	—	—	98·6
" Lipari ..	*c.*	74·05	12·97	0·12	0·28	5·11	4·15	—	2·73	—	—	(Cl. 0·28)	99·94
Trachyte, Drachenfels ..	*d.*	65·07	16·13	2·74	0·67	4·44	4·47	.	5·17	—	0·70	—	99·96
" Tokay ..	*e.*	60·74	14·8	4·88	..	0·38	8·65	..	7·40	..	1·35	—	99·44
Andesite, Guatemala ..	*f.*	67·91	17·38	2·80	1·35	1·84	5·43	1·25	1·77	0·06	—	Zi. 0·06	99·83
Pumice, Santorin ..	*g.*	69·79	12·31	1·68	0·68	2·02	6·69	—	4·66	—	—	Cl. 2·93	100·76
Phonolite, Mont Dore ..	*h.*	59·84	23·07	1·48	0·25	4·13	4·52	trace	3·35	trace	3·20	—	99·84
Basalt, Staffa	*i.*	44·50	16·75	9·50	2·25	..	2·60	$\underbrace{\qquad\qquad}_{20·20}$		0·12	2·00	—	97·92
* " Rossdorf	*j.*	40·53	14·89	14·62	8·02	1·95	2·87	11·07	1·02	0·16	—	Co. 0·17 Ph. 1·32	99·86
Lava, Vesuvius, 1631 .. (with crystals of Olivine)	*k.*	48·12	17·16	9·84	3·99	7·24	2·77	5·13	5·69	1·20	0·08	Ti. 0·22	101·44
Lava, Vesuvius, 1858 .. (with crystals of Leucite)	*k.*	46·36	18·60	9·09	4·00	7·18	2·96	4·94	4·12	1·00	0·40	Ti. 0·29 Fl. 0·06	99·00
Lava, Ætna, 1865 ..	*l.*	49·27	18·54	10·38	3·76	2·22	3·45	5·62	6·98	—	—	Cl. 0·14	100·36
" Teneriffe	*m.*	48·64	22·92	9·02	3·91	1·04	1·89	5·98	5·07	0·14	—	Ti. 0·37	100·19
" Auvergne (Gravenoial)	*n.*	48·57	19·47	10·86	4·25	0·82	1·33	13·53	..	0·76	0·48	—	99·82
" Eifel?		48·94	11·56	16·8	5·98	2·82	3·46	—	15·26	—	2·17	—	106·27
" Hecla (Iceland)	*p.*	49·60	16·89	13·07	7·56	0·20	1·42	11·92	—	—	—	—	100·66
" Aden	*q.*	46·70	11·70	7·92	11·31	0·77	5·97	8·40	2·74	0·26	..	Ti. 1·41	97·18

a. Sommaruga. *b.* Vauquelin. *c.* Abich. *d.* C. Deville. *e.* Bernath. *f.* Marx. *g.* Abich. *h.* Genth. *i.* Kennedy. *j.* Petersen. *k.* Haughton. *l.* Petersen. *m.* Wartha. *n.* Lassaulx. *p.* Genth. *q.* Haughton.

[1] But having been more fluid or flowing, as its name implies.

It is much more difficult, owing to the fineness of the grain of most of these rocks, to determine, unless by sections under the microscope, the character and proportions of the constituent minerals of which the above analyses give the ultimate elements. Attempts have been made by apportioning the constituent elements of the rock, as in the case of the Rossdarf basalt, to determine its mineral constituents. By this means they were estimated to be in the following proportions:—

Anorthose (Labradorite)	46·36 parts
Augite	27·40 „
Peridot (Olivine)	17·60 „
Titaniferous Iron	4·86 „
Apatite	3·23 „
Carbonate of Lime	0·40 „
	99·85

Dr. Haughton and Professor Hull have also sought to show, in an elaborate paper[1], that, the constituent minerals having been first determined by the microscopic examination of thin slices of the rock, it is possible, by a series of equations constructed by Dr. Haughton, so to apportion the several elements, as to give the relative proportions of the minerals present in the rock. These being eliminated, the residual quantities are supposed to constitute a paste, in which the minerals are imbedded; and this paste is found to consist, in general, of a very fusible basic glass, with a large proportion of iron protoxide. By this means, the authors determined the mineral composition of twenty Vesuvian lavas. Those of two lavas erupted at long intervals of time are as follows:—

	I. *Di Gravina*, 1631.	II. *Fosso Grande*, 1858.
Leucite ...	38·2	40·8 parts
Anorthite ...	6·6	12·3 „
Magnetite ...	7·14	4·86 „
Olivine ...	traces	trace „
Augite ...	28·6	28·6 „
Hornblende ...	trace	... „
Mica ...	„	... „
Nepheline ...	10·5	... „
Sodalite ...	trace	7·1 „
Apatite ...	„	... „
Paste ...	8·96	6·34 „
	100·00	100·00

The chemical composition of the paste in each case is,—

	I.	II.
Silica ...	46·9	42·4 „
Lime ...	25·0	25·8 „
Protoxides (iron chiefly) ...	28·1	31·8 „
	100·0	100·0

M. Fouqué adopted a mechanical plan for ascertaining the minerals present in the lavas of Santorin; and which admits of an approximate

[1] 'On the Characters of the Lavas of Vesuvius.' Trans. Roy. Irish Acad., vol. xxvi. p. 49, 1876.

determination of their constituent parts. He first reduced the rock to a coarse powder. To this is applied a powerful electro-magnet (one of Bunsen's), which removes all the ferruginous elements and leaves a nearly pure white powder. In this the different sorts of felspar may sometimes be distinguished at once; at other times by their different solubility in hydrochloric acid, or, better still, in hydrofluoric acid, which leaves the iron oxides, augite, and olivine. The iron minerals are then removed by a magnet. The pyrites and iron oxide can be distinguished with a glass, or the latter may be removed by weak sulphuric acid. The amorphous matter can be treated in the same way, but is of more difficult determination. In this way M. Fouqué found that there were three varieties of felspar, and several varieties of iron oxides and pyrites in the Santorin lavas.

2. *Plutonic Rocks.*

THE FELSPAR GROUP.

These, like the foregoing, are divided, according to the preponderance of felspathic or amphibolic constituents, into two groups. The common rocks of the first or felspar-group are,—

1. **Granite**[1].—A crystalline admixture of felspar, quartz, and mica in distinct parts. The mica is usually dark-coloured, but may be light-grey, yellow, green, or white. The felspar may be opaque white, rose, red, or grey, and is usually of the variety termed orthoclase. The quartz is more or less limpid or white. Ex. *The Grey Granites of Aberdeen and Dartmoor; the Red Granite of Peterhead.*

When the granite contains large, distinct, disseminated crystals of felspar, it is termed '**porphyritic Granite**.' Ex. *The Granite of Lamorna, Cornwall; Shap, Cumberland.*

Sometimes the mica is replaced by massive crystals of black tourmaline or schorl, and such portions of the rock have been called schorlaceous granite or **Luxullianite.** Loc. *Luxullyan, Cornwall.*

2. When the mica is replaced by hornblende, the rock is termed a Syenite or a **Syenitic granite**, though the term syenite is now by many geologists confined to an admixture of felspar and hornblende alone. Ex. *Syene, Egypt; Skye; Central axis of the Vosges.*

3. **Protogine.**—A granite in which the mica is replaced altogether or in greater part by talc. Loc. *Central axis of Mont Blanc; Tyrol.*

4. **Pegmatite** consists essentially of felspar (generally very crystalline), with quartz, usually limpid, mica accidental. When the quartz is in parallel lines, a transverse section shows them in forms resembling Hebrew characters, whence termed '**Graphic Granite**.' Loc. *The Pyrenees; Saxony; Ceylon.*

5. **Leptynite** (**Granulite** of some authors), a name sometimes given to a very fine-grained granite, having the aspect of sandstone, and composed almost entirely of orthoclase felspar and quartz. Loc. *Dartmoor; St. Gothard; Cherbourg; Saxony.*

[1] As will be explained further on (Chapter xxiii.), granite, although placed here amongst the Plutonic rocks, is not to be considered a truly igneous rock in the strict meaning of the term.

6. **Greisen.** A mixture of granular quartz and mica. Loc. *Cornwall; Saxony.*

7. **Syenite** (of some authors).—A crystalline or granular admixture of felspar (usually orthoclase of a reddish colour) and hornblende[1]. Loc. *Markfield and Grooby, Leicestershire; Saxony; the Channel Islands; Malvern.*

8. **Porphyry** (Felspar-Porphyry, Porphyrite).—An amorphous felspathic base, commonly dark red, sometimes green, with disseminated crystals (usually of a lighter colour) of felspar (generally oligoclase[2]). Ex. *Pentland Hills; Norway; the Ardennes; Saxony.*

9. When, in addition, crystals of hornblende are present, it is termed '**Hornblende-Porphyry.**' Ex. *Red Egyptian Porphyry; Cader Idris; Lugano; Dresden.*

10. When mica is present '**Mica-Porphyry**' (Minette). Loc. *Thuringian Forest; Vosges; Sweden.*

11. **Granitic Porphyry.**—A matrix (commonly red or green) of felspar, with imbedded crystals of felspar, quartz, and mica, or chlorite. Loc. *Camelford, Cornwall; Saxony; Thuringian Forest.*

12. **Quartz- or Quartziferous Porphyry** (Elvanite).—A felspathic base with crystals or crystalline grains of felspar and quartz. Ex. *Dykes or Elvans of Cornwall; Var., the Palatinate.*

13. **Felstone** or **Felsite** (**Eurite** and **Petrosilex** of continental geologists).—An intimate mixture of felspar and silica, forming a compact rock, chiefly of dull, opaque yellow, grey, red, or green colours. It might at times be mistaken for a metamorphic quartzose rock, but is readily distinguished by its easy fusibility, relative hardness, and its weathered bleached surfaces. Loc. *Common among the Silurian rocks of Wales and Cumberland; the Pyrenees; the Alps.*

Hälleflinta is a flinty, fissile or laminated variety of felstone.

14. **Pitchstone** (**Retinite**).—Similar in composition to the [illegible], but occurring in a vitreous or glassy state. It is of variously coloured red, yellow, green, brown, and black; it is sometimes porphyritic, and often shows spherulitic structure. Ex. *Dykes through the Red Sandstone of the Isle of Arran; Cantal; Hungary.*

THE AMPHIBOLE GROUP.

The rocks of this group are sufficiently characteristic when the crystals are of a size to be distinct, but when, as frequently happens, the grains are so fine as not to be distinguishable to the eye, these rocks so closely resemble one another, that they have been commonly simply designated from their dark-greenish colour 'Greenstones.'

1. **Diorite** (Ophite).—A granular compound, often in distinct grains, of triclinic felspar (generally oligoclase) and dark-green hornblende; not unfrequently passes into an amorphous, compact, fine-grained rock. Loc. *Cader Idris, Wales; St. Mewan, Cornwall; Corsica; the Morea.*

2. **Diabase.**—A granular mixture of triclinic felspar with augite and some chlorite. Colour usually dark-green. Loc. *Dolgelly; Cumberland; Scotland.*

3. **Gabbro** (**Euphotide**).—A mixture chiefly of felspar (labradorite) and diallage, varying from granular to compact. Loc. *Monte Rosa; Mont Cenis; Skye.*

[1] There is a want of agreement amongst petrologists as to the definition of syenite. The typical syenite of Egypt contains quartz.

[2] Altered (earthy) porphyries used to pass under the name of 'Claystones.'

4. **Norite**—is a term commonly used to embrace those varieties of this group of rocks in which hypersthene, enstatite, olivine, quartz, and mica enter in various proportions. Loc. *Norway; the Eifel.*

THE MAGNESIAN GROUP.

Serpentine (Ophiolite, Brongniart).—A hydrated silicate of magnesia, with crystals of diallage and bronzite. It forms a dark, mottled, green, red, and black rock, is unctuous to the touch, and is cut easily with a knife. Loc. *The Lizard, Cornwall; Portsoy, Banffshire.*

Lherzolite, Pikrite, and Dunite belong to this group, to which the name of 'Peridotites' has been given.

The following Table gives the ultimate chemical analysis of some of the principal of these Plutonic rocks.

	Silica.	Alumina.	Lime.	Magnesia.	Potash.	Soda.	Iron-protoxide.	Iron-peroxide.	Manganese-protoxide.	Water.	Totals.
Granite, Grey, Gready, Cornwall *a.*	69·64	17·35	1·40	0·21	4·08	3·51	1·97	1·04	trace	1·09	99·92
„ Red, Peterhead *a.*	73·70	14·44	1·08	trace	4·43	4·21	1·49	0·43	trace	0·61	100·39
„ Cud. Malin, Ireland. *b.*	70·00	16·36	1·12	0·71	4·66	4·13	0·08	2·80	—	—	99·88
„ Grey, Hartz .. *c.*	75·46	11·89	1·25	0·08	4·40	2·56	3·52	—	—	1·12	100·28
Felsite, Brittany .. .. *o.*	75·40	15·50	..	1·40	3·80	..	1·20		..	..	97·30
„ Dopenheim .. *m.*	77·42	10·00	0·76	0·36	5·20	1·13	..	2·69	..	1·15	99·21
Pitchstone, Arran .. .. *q.*	73·00	12·27	0·50	—	4·32	3·64	1·50	—	—	5·12	100·00
Quartz-porphyry, Germany. *p.*	78·86	11·12	0·13	trace	8·03	1·22	0·22	0·93	..	0·37	100·88
Porphyry, Red, Egypt . *d.*	62·17	14·71	3·30	5·00	2·04	4·10	—	7·79	trace, loss	0·58	99·66
„ St. Just en Chevalet, *f.*	62·30	19·70	4·50	1·10	3·45	2·57	—	4·20	—	1·90	99·72
Syenite, West Aston .. *b.*	52·08	15·60	6·52	8·40	3·80	2·92	2·57	5·75	..	2·24	99·88
Euphotide (Gabbro), Vicentin *g.*	50·32	16·22	10·72	8·21	1·07		5·60	4·74	..	1·88	99·67
Gabbro, Hartz .. .. .. *e.*	53·65	20·77	9·76	1·57	1·61	3·33	7·61	0·98	—	1·33	100·01
Melaphyre, Spiemont .. *l.*	51·62	20·44	1·39	4·38	4·22	5·81	5·15		..	3·91 TiO² 0·96	100·04
Diorite, Hartz .. .. .. *c.*	51·07	22·12	6·11	2·09	3·25	4·11	9·28	—	—	1·21	99·24
„ St. Mowan.. .. *a.*	47·66	17·50	4·20	—	2·43	5·10	9·42	12·52	—	0·83	99·91
Trap, Sweden .. .. .. *k.*	50·22	14·97	10·48	5·76	1·62	2·20	15·76	..	1·13	0·70	102·64
Rowley Rag, Dudley .. *i.*	49·86	12·75	8·71	4·39	0·57	5·25	11·38	3·36	Tra., 1·33	Ph. 0·58 2·50	100·74
Diabase, Bohemia .. Etage D. Sil., Barrande *h.*	45·53	15·07	10·11	1·05	trace	3·55	19·26	—	— a loss	5·30	99·87
Serpentine, Lizard .. .. *a.*	38·80	2·95	—	34·61	0·33	0·77	5·04	1·86	Cr^2O^3. 0·08 NiO. 0·28	15·52	100·24
„ Levanto.. .. *n.*	40·47	4·35	0·84	34·59	..	..	7·61		0·15	11·61	99·62

a. J. A. Phillips. *b.* Haughton. *c.* Fuchs. *d.* Delesse. *e.* Streng. *f.* Levy. *g.* Young. *h.* Fellner. *i.* Henry (Forbes). *k.* Franke. *l.* Kosmann. *m.* Trilobet. *n.* Bonney. *o.* Durocher. *p.* Gumbel. *q.* Lassaulx.

The larger size generally of the constituent minerals in plutonic rocks renders their determination easy; but in those where the grain is fine, their determination, as in the volcanic rocks, becomes more difficult. To ascertain these relative proportions M. Delesse[1] employed an ingenious

[1] 'Procédé mécanique pour déterminer la Composition des Roches;' Paris, 1866.

mechanical contrivance, by means of which he obtained the following results:—

Red Granite.
Egypt.

Felspar { Red Orthoclase	43 parts.
Felspar { White (Albite?)	9 „
Grey Quartz	44 „
Black Mica	4 „
	100

Porphyritic Granite.
The Vosges.

White Orthoclase	28 parts.
Reddish Oligoclase ...	7 „
Grey Quartz	59 „
Mica	6 „
	100

Porphyries.

Red (Antique).

Rose-coloured Oligoclase	11 parts.
Hornblende	2 „
Maroon-red Paste ...	87 „
	100

Green.

Greenish Felspar (Labradorite)	42 parts.
Green Paste	58 „
	100

Diorites.

	Large grained.	*Orbicular*, Corsica.
White Albite with a little quartz ...	64 parts	84 parts.
Green Hornblende	36 „	16 „
	100 „	100 „

According to Dr. Haughton the *Leinster Granite* is composed of—

Quartz	parts 32·57 per cent.
Felspar { Orthoclase	„ 15·44 „
Felspar { Albite	„ 22·10 „
White Mica (Margarodite)	„ 19·16 „
Black Mica (Lepidomelane)	„ 5·81 „
Paste (Silicate of Lime)	„ 4·92 „
	100·00

Number of Rock Species. The lists in the foregoing pages embrace all the chief orders of rocks more commonly met with. Taking all the varieties, the total number of rocks entering into the composition of the earth's crust may amount to between 200 and 300. The indefiniteness of these numbers arises from the difference of opinion amongst petrologists as to what constitutes a typical rock, and where to draw the line between the several groups. With the sedimentary strata, which are derived from the materials of pre-existing rocks, there is little difficulty, as they consist of mechanically sorted constituents which, though in variable proportions and in various degrees of solidification, are for the most part easily recognisable and one sort usually predominates. But when instead of a mechanical arrangement of a few simple minerals, we have, in rocks of igneous and metamorphic origin, a variety of minerals intimately combined in various proportions, their determination becomes a very different and often a very difficult problem.

Use of the Microscope. When the several minerals have crystallised or separated out in distinct parts, as in granite, porphyry, etc., the determination is easy. But when the various silicates, many of them so nearly

allied in composition, are blended together into masses so compact and fine-grained as to render the separate grains invisible to the naked eye, it requires all the care and skill of the accomplished petrologist to distinguish their characters, and to determine accurately their constituent parts. Experience may enable the practical geologist to recognise, by external and general characters, all the more ordinary of these rocks. But when the many varieties present themselves, and it becomes a question of distinguishing between the several felspars, amphiboles, pyroxenes, etc., in an apparently homogeneous rock, no character sufficiently tangible offers itself to the unassisted eye. Nor is chemical analysis of much avail, for in those cases where the grains are so fine that it is impossible to separate the component minerals, we can only obtain the analysis of the whole mass, or that of the sum of all the minerals, in place of their individual constitution. The elements may vary but little, as the analyses at pp. 37, 41 show, and yet the constituent minerals may vary greatly, in consequence of the elementary substances combining in different ways, and giving rise to different mineral species[1].

As an adjunct, therefore, to chemical analysis, the microscope has of late years been brought much into use by petrologists, and with great advantage. For all rocks which have undergone igneous or hydro-igneous fusion, however fine, homogeneous, and compact they may appear to the eye, really consist of an aggregation of minute crystals and grains distinguishable with the aid of the microscope when the rock is cut into slices sufficiently thin to be transparent. Hence by these means the optical and crystallographical characters of the several constituent minerals may be more or less readily recognised. This, however, is an expensive and tedious process; and to the geologist in the field a thin splinter of the rock, or the powder of a crushed fragment examined under a strong lens, affords the most ready and available plan for a preliminary determination of the rocks.

There are also certain general characters useful as a guide in the recognition of rocks of igneous origin, such as their mode of weathering, the frequent bleaching of their exposed surfaces, the absence of sand and of calcareous cement, etc., their not unfrequent decomposition even to considerable depths from the surface, and their general fusibility before the blowpipe.

The metamorphic rocks often present characters very analogous to those of the plutonic rocks; but, as a whole, they are less felspathic and less fusible; while, notwithstanding the extreme alteration they have in many cases undergone, and their crystalline structure, traces of the original bedding may generally be detected. Metamorphic action has necessarily

[1] More might possibly be done with the chemical analyses by apportioning the elements in accordance with their atomic weights and combining proportions.

mainly affected the older and lower strata. Nevertheless, there are many exceptions; as, for example, in the case of the well-known Carrara marble, a limestone of Triassic age, which in the Apuan Hills, near Pisa, has been converted by metamorphic action into a fine granular crystalline rock; and in the equally remarkable case of strata of Eocene age, which at the Diablerets above Bex, in the Swiss Alps, are changed into slates as compact and hard as the old Cambrian rocks of Wales. The Glaris slates are of Cretaceous age; many other instances might also be mentioned.

Nor does it always happen that the older strata are altered or metamorphosed; for the Silurian rocks of Northern Russia yet remain as earthy and unchanged as many tertiary strata.

Stratigraphical divisions of the Rocks. The rocks of the sedimentary strata, which we have described in the first part of this chapter, and which constitute the thin outer film of the solid crust of the earth, do not occur indiscriminately distributed, but are arranged in definite order.

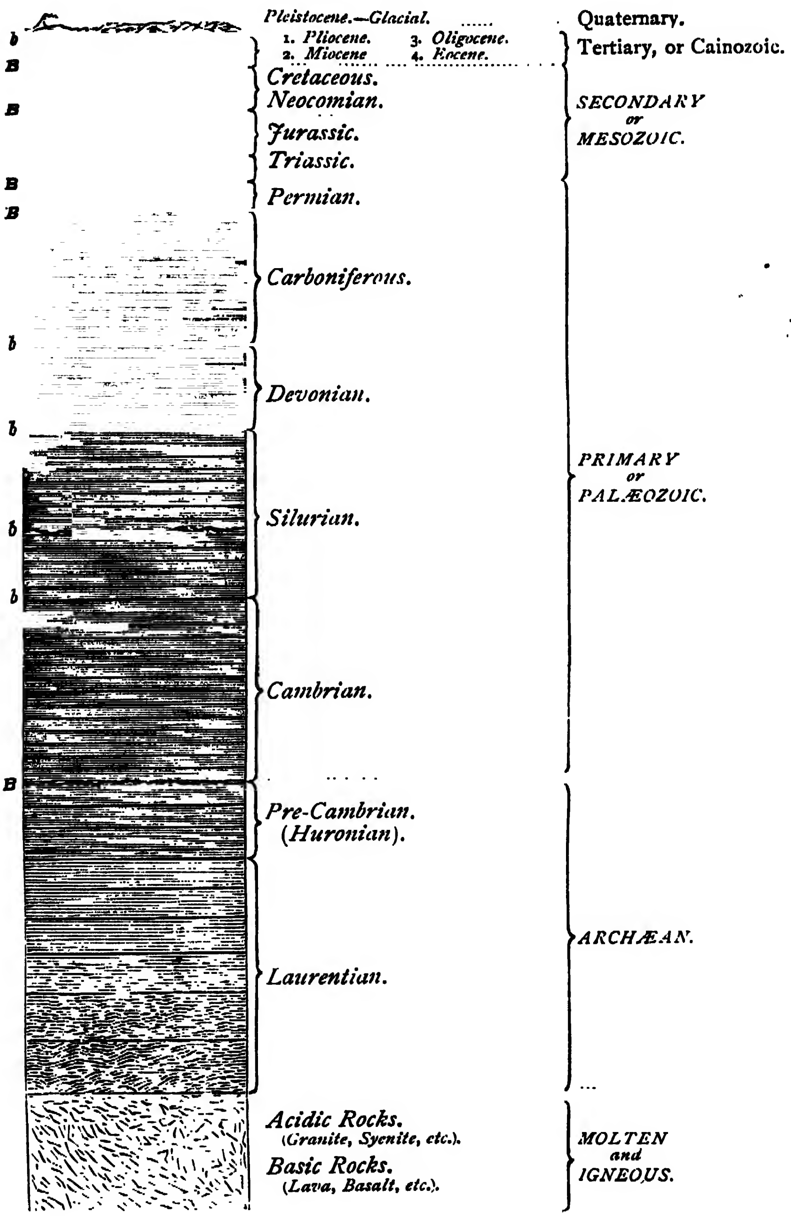
Leaving the rocks of igneous origin for the present, we will first take the sedimentary deposits, and see what may have been their origin and what is the nature and relation of their fossils[1]. These deposits consist of regular layers or strata, lying one over the other, and these are grouped into divisions or *Formations* of variable thickness, each characterised by peculiar organic remains; and these Formations, whenever occurring, always bear the same relative position one to another. Geologists have divided the sedimentary strata, of which the total thickness amounts on the whole to not less than twenty to twenty-five miles, into about forty *Formations* of very variable dimensions; and these again are grouped into the Series and Periods shown in the following diagram.

The reader will however understand that the entire series, as here exhibited, is never found in complete sequence. Some members are wanting in one place and some in another, but the order of sequence is always the same and always maintained. Where there are missing links there is a physical and palæontological break of a more or less marked character (*B*, *b*, Fig. 13). The larger divisions here given are of universal application: the lesser groups, which are of more local occurrence, and have regional limits and distinctions, will be described in the section on Stratigraphy in the next part of this work.

Map of the World. The general character and age of the strata in all parts of the civilised world are now pretty well known, although much remains to be done in filling up the details. Professor Jules Marcou reduced all the available information on this subject to a uniform plan, and

[1] For a brief epitome of the rocks and fossils the student will find Morris's and Rupert Jones's 'Geology' a concise and useful guide.

FIG. 13. DIAGRAM SECTION SHOWING THE SUCCESSION OF THE SEDIMENTARY SERIES, AND THE GREATER GENERAL GEOLOGICAL DIVISIONS.



B marks the larger *breaks*, and *b* the smaller breaks, in time. The Igneous rocks are represented in their supposed normal position under the Sedimentary Strata, but in speaking of them they are said to be of the age of any of the strata forming at the time of their protrusion through them.

published a few years since a geological map on a large scale (of which the Frontispiece to this volume is a small reduction), showing the range of the chief groups of strata in both hemispheres. Their relative importance is thus seen at a glance. The great extent of the crystalline and lower palæozoic rocks is a striking feature, as is also the large development, in the North-Western America and East-Indian areas, of volcanic (basaltic) rocks. In this reduction I have had, owing to the small scale of the map, to unite under one colour the Cretaceous and Jurassic series, otherwise I have mainly adhered to M. Marcou's divisions and names, with the exception of the term Dyas for the Permian. I have retained the latter term, as the one more generally known and accepted in England. M. Marcou and Prof. Geinitz, who consider that the term Permian involves stratigraphical errors, some years since proposed the word 'Dyas' for strata very much the equivalent of what Sedgwick comprehended in his lower 'New Red Sandstone.' The distribution of the great stratigraphical divisions given in Fig. 13 will be readily seen by reference to this map.

CHAPTER IV.

RESULTS OF THE DECOMPOSITION OF THE IGNEOUS AND METAMORPHIC ROCKS.

CHEMICAL CHANGES EFFECTED BY WEATHERING OF THE ROCKS. DECOMPOSITION OF THE FELSPARS. FORMATION OF KAOLIN. ORIGIN OF CLAYS. DECOMPOSITION OF OTHER SILICATES. LIBERATION OF THE EARTHS AND METALLIC OXIDES. ORIGIN OF CALCAREOUS MATTER AND OF ALKALINE SALTS. ORIGIN OF SANDSTONES. EXTENT OF ROCK-DISINTEGRATION. SURFACE-DISINTEGRATION OF GRANITE, GREENSTONES, SERPENTINE, BASALTS. SEDIMENTARY ROCKS LESS SUBJECT TO DISINTEGRATION. SECONDARY PRODUCTS. IMPORTANCE OF THIS SUBJECT IN QUESTIONS OF DENUDATION AND TIME.

IN the last chapter it was shown that one class of rocks—those of igneous origin which must have formed the original outer shell, and were afterwards, from time to time, protruded through the superimposed strata —consist, in greater part, of various silicates of the earths, alkalies, and metallic oxides, which are largely subject to external atmospheric influences. In consequence of this, these rocks, hard and seemingly indestructible as they generally are in their unaltered state, are liable to decompose and disintegrate into soft and yielding masses.

As all the sedimentary strata are derived from the wear and reconstruction of others of older date,—all traceable back to the antecedent igneous rocks,—these changes in the structure of the latter, not only bear upon the composition of the former, but the subject involves also considerations relating to the phenomena of *denudation* and *time* that must be kept in view in the discussion of several important problems of physical and theoretical geology. The processes of decay in facilitating the wear of rocks are not less important than that of erosion in effecting their removal; for the extent and rate of denudation are necessarily dependent upon the resistance offered by the surfaces undergoing denudation; and this resistance is essentially contingent upon the amount of disintegration caused by those chemical changes to which especially the rocks constituting the original framework of the globe have ever been liable.

Chemical Changes affecting Igneous Rocks[1]. It follows from what has been said of the composition of the sedimentary and igneous rocks that the insoluble essential bases of both are alike,—only that in the former they exist free, and in the latter usually combined. Nor is it difficult to trace back to the igneous rocks the materials composing the sedimentary strata. We have seen that all the rocks of igneous origin, to whichever class they belong, consist of silica, sometimes free (quartz), but more generally in combination with the various earths and alkalies, and a few metallic oxides, forming with them a variety of silicates, amongst which the felspars very largely predominate. The felspars are essentially double silicates of alumina, and of the alkalies and alkaline earths. They contain more or less potash or soda, and form more or less stable compounds in proportion to the quantity and nature of the alkalies present. Their composition varies in consequence of the bases being liable to be in part replaced by one another; the typical composition of the three geologically more important varieties has been given at p. 14. These contain silica, alumina, potash, soda, and lime in variable proportions.

Formation of Kaolin. Exposed to the action of the weather, the felspars of the hardest granites, and of the analogous crystalline rocks, are, under certain conditions, decomposed by the carbonic acid in the rain and surface-waters, forming, with the lime and alkalies present, carbonates, which, being readily soluble, are, with probably some alkaline silicates, removed wholly or in greater part by the water; while the silica set free remains mostly as an impalpable powder. The combination of silica and alumina on the other hand being entirely insoluble, remains, combined with a portion of water which is taken up during the change, and the resultant is a white mealy powder, unctuous and plastic in water. This is a hydrated silicate of alumina, or kaolin (China-clay), of which the normal composition in a pure state is—

$$\left.\begin{array}{ll} \text{Silica} & 46.4 \\ \text{Alumina} & 39.7 \\ \text{Water} & 13.9 \end{array}\right\} \text{ or } Al^2O^3.\ 2SiO^2 + 2HO.$$

$$\underline{}\quad 100.0$$

This change shows the loss of a portion of the silica and of all the alkalies; while the whole of the alumina, in combination with the other portion of the silica, remains as an insoluble residue, holding a definite proportion of combined water. But, as there generally remains some portions of undecomposed felspar and a variable quantity of free silica, the actual composition in nature varies within certain limits, as the following analyses of kaolin from different localities show.

[1] The reader should consult on this subject Bischof's 'Chemical and Physical Geology,' and Sterry Hunt's 'Chemical and Geological Essays.'

	1. Dartmoor.	2. Limoges. (*Forchammer.*)	3. Japan. (*Wurtz.*)	4. China. (*Ebelmen.*)	5. Lombardy. (*Curioni.*)
Silica	47·20	48·68	49·93	50·5	60·20
Alumina ...	38·20	36·92	38·74	33·7	26·52
Lime	...	...	...	...	0·86
Magnesia ...	...	0·52	0·21	0·8	trace
Potash... ...	2·00	...	0·44	1·9	...
Soda	...	0·58	1·44	...	...
Iron-peroxide	...	...	1·58	1·8	1·97
Water	12·74	13·13	7·61	11·2	8·50
	100·14	99·83	99·95	99·9	98.05

Nos. 1 and 2 are derived from decomposed granite, No. 2 from pegmatite, and No. 5 from a porphyry.

Almost all the China-clays contain, therefore, with a definite hydrated silicate representing the typical kaolin, small portions of the other elements present in the original rock.

Origin of Clays. This kaolin is the basis of all clays; and where the decomposed rock contains foreign elements, the clays show corresponding varied composition. There are some, however, and the following are instances, which approach very closely to the purer kaolins, having possibly been derived direct from old granitic areas.

	1. Miocene beds, Bovey Tracey.	2. Eocene beds, Poole. (*Percy.*)	3. Coal-Measures, Sheffield. (*Percy.*)	4. Tertiary, Abondant, near Dreux. (*Berthier.*)	5. Carboniferous, Angleur, near Liege.
Silica	49·60	48·99	48·04	50·6	46·9
Alumina ...	37·40	32·11	34·47	35·2	36·4
Lime	...	0·43	0·66	...	—
Magnesia ...	...	0·22	0·45	...	1·0
Potash... . .	...	3·31	1·94	...	—
Soda	...	—	...	...	—
Iron-protoxide	...	2·34	...	0·4	—
„ peroxide	...	...	3·05	...	—
Water	11·20	11·99	11·15	13·1	14·8
	98·20	99·39	99·76	99·3	99·1

Granite and its ally pegmatite furnish the purest kaolins. Kaolin is also obtained from decomposed porphyries and gneisses.

The decomposition is not limited to the felspars. It equally affects the other silicates which enter so largely into the composition of the more basic igneous rocks; and, as in these rocks free quartz is generally absent, the whole mass disintegrates and decomposes. These silicates contain also other elements besides those yielded by the felspars, and add therefore to the variety of substances entering into the composition of the sedimentary strata.

Decomposition of other Silicates. The composition of the more important of the basic rocks has been given in Chapter II. The normal composition of the silicates other than the felspars which form the more essential and constant constituents of these rocks is as under.

	Hornblende.	Augite.	Olivine.
Silica	48·8	54·1	38·5
Alumina	7·5	...	0·2
Lime	10·2	23·5	...
Magnesia	13·6	11·5	48·4
Iron-protoxide ...	18·75	10·0	11·2
Manganese-oxide	1·15	0·6	0·3
	100·00	99·7	98·6

These rocks furnish, therefore, by their decomposition, not only kaolin together with lime and magnesia, but also a large proportion of the peroxide of iron resulting from the peroxidation and hydration of the protoxide; while a hydrated silicate of the protoxide of iron is formed as another product of the alteration of the hornblendes and augites. It is in this way that the widely disseminated iron-peroxides, and glauconite (silicate of iron), so abundant in many of the sedimentary strata, have originated.

It is owing to the presence of these complex silicates containing lime, magnesia and the metallic oxides, that diorite, diabase, melaphyre and other basic rocks generally decompose into green and brown clays. Great bodies of these rocks are also often converted into masses of soft and decayed rock, of grey, green, red, or brown colours, formerly known under the general name of 'wacké.' At Robschutz in Saxony a decomposed diorite is worked as a fuller's earth, and near Florence a decomposed variety of gabbro is worked as a fire-clay [1]. The vitreous varieties of these rocks, retinite and pitchstone, do not so readily decompose, but such instances do occur as will be mentioned further on. Claystones are altered felspathic and porphyritic rocks.

Serpentine—itself an altered rock—is not unfrequently more completely decomposed and changed into magnesian clays, sometimes white and at other times coloured. Some of these clays contain as much as 33 per cent. of magnesia.

The following is the composition of some earthy rocks and clays, derived from decomposed magnesian rocks. (See the chemical analyses of the unaltered rocks given at p. 41.)

[1] C. D'Orbigny, *Op. cit.* pp. 262–3.

	1. Soft Wacké, Seigen. (*Berthier.*)	2. Decomposed Serpentine, Central France.	3. Magnesian Clay, Styria. (*Hauer.*)	4. Magnesian Clay, Tertiary Strata, Saint Ouen. (*Berthier.*)	5. Fuller's Earth, Silesia.
Silica	61·4	42·00	59·2	51·0	48·50
Soluble Silica	4·5	—	—	—	—
Alumina ...	20·8	—	14·0	14·0	15·50
Lime	—	—	trace	—	—
Magnesia ...	2·8	30·50	6 2	13·4	1·50
Potash... ...	7·5	—	—	—	—
Iron-peroxide	—	15·00	trace	3·0	7·00
Water and loss	3·0	12·50	20·3	18·2	25·50
	100·0	100·00	99·7	99·6	98·00

This alteration in the felspathic bases under the influence of atmospheric agencies is very noticeable in the basaltic rocks; and, as these, like the older greenstones, contain silicates with metallic oxides, they only furnish very impure clays. The decomposition of the hornblende, augite, olivine, etc. in such rocks liberates, in addition to the silica and alumina, proportions of lime, magnesia, iron, manganese, etc., which latter variously modify and colour the clays. To take, for instance, the clays resulting from the decomposition of two basalts. (For the composition of undecomposed basalt see p. 37.)

	1. Basalt-clay, Annaberg. (*Roth.*)	2. Basalt-clay, Silesia. *Büttner.*)	3. Red clay[1], Coal-measures, Broseley. (*D. Forbes.*)
Silica	40·352	53·01	64·06
Alumina	32·515	14·49	20·60
Lime	3·727	2·85	0·12
Magnesia	1.277	2·39	00·4
Potash...	0·365	0·19	0·91
Soda	1·311	0·25	0·44
Iron-peroxide ...	9·170	...	6·84
„ protoxide ...	...	14·87	0·32
Manganese	0·034	—	0·09
Titanic acid ...	1·461	—	0·62
Water and loss ...	9·646	10·65	5·85
	99·858	98·70	99·89

In No. 1, abstraction being made of the metallic oxides, the clay has the formula (nearly) of $Al^2 O^3, 2\, Si O^3 + 2\, HO$, which is that of kaolin. In No. 2 free silica is largely in excess.

The red clays of the Coal-measures and other strata, in which both

[1] This clay also contains 0·11 of bisulphide of iron, and 0·07 of sulphate of lime.

manganese and titanic acid are also frequently met with, much resemble in their composition some of these basalt-clays, and were probably derived from some similar older rocks. No. 3 is one of these clays of which the analysis is given by Mr. Maw. Other basic volcanic rocks, such as dolerite, andesite, etc., are also liable to decompose; and so also in a lesser degree are the trachytic lavas and scoriae, which latter, however, give rise to light-coloured clays—sometimes as white as chalk. The village 'Bianca,' in the volcanic country near Rome, derives its name from the whiteness of the soil produced by the kaolin resulting from the decomposition of trachyte. Trass is a grey or whitish volcanic tufa, common in many volcanic districts, resulting from the decomposition of trachytic cinders, just as peperino, which is a darker tufa, results from the decomposition of the ashes and cinders of basic lavas: in both cases the decomposed mass has often been subsequently solidified by the infiltration of calcareous or siliceous matter in solution.

The vitreous lavas are less liable to decompose. Obsidian is rarely altered; and fragments of pumice, dredged up from great depths by the 'Challenger' Expedition, exhibit no alteration, and are as fresh as if from a recent eruption.

As all ordinary clays consist of a base of hydrated silicate of alumina mixed with a portion of impalpable free silica, and various impurities derived from the several associated minerals in which lime, magnesia, iron, and manganese, etc. are present, there can be little doubt that their origin is to be traced to the decomposition of the older volcanic and plutonic rocks. Generally, however, they are not derived direct from the parent rock, but are reconstructed, especially in the later deposits, from older clay beds.

Origin of Calcareous Strata. Besides the foregoing insoluble residues set free by the decomposition of the felspars and other silicates, there are certain soluble bases liberated at the same time, consisting of the various alkalies and earths, and these, combining with the carbonic acid with which the decomposing waters are charged, pass off as soluble carbonates into the surface and underground waters.

A certain portion of the silica, freed or in combination with a base, is also taken up by the water. This accounts for the apparent gain of the alumina in relation to the silica in most of these residues. The annexed tables show the effect of these changes in the two classes of rock.

The first analysis is that of a disintegrated fine-grained Granite of orthoclase felspar, with black and white mica, from Hanzenberg in Bavaria; it exhibits the loss of the soluble alkalies and the relative gain in some of the other substances, though not the possible extent of change, as the decomposition is only partial.

When oligoclase or albite is present, lime and a larger proportion of

	Granite (André). Unaltered.	Disintegrated.	Difference.
Silica	73·13	74·57	+ 1·44
Alumina ...	10·50	12·02	+ 1·52
Magnesia ...	1·12	0·80	− 0·32
Potash...	9·04	4·92	− 4·12
Soda	1·80	0·46	− 1·34
Iron-peroxide	3·16	3·20	+ 0·04
Water	0·45	3·20	+ 2·75
Loss	0·80	0·83	+ 0·03
	100·00	100·00	

the alkalies are liberated. An altered gneiss of Erzgebirge in Saxony was found to have lost—silica 1.0, lime and magnesia 1.0, potash and soda 3.6 per cent., and gained water 3.0; while a decomposed porphyry from Finland showed a general loss of lime, potash, soda, iron-oxide, and silica.

Ebelmen has shown what the loss of soluble matter is in some basic rocks; and, as he reduces the various constituents to a definite proportion of alumina, that substance being the only fixed residue, the importance of the difference between the altered and unaltered rock becomes more apparent. Thus the change in two varieties of these rocks is as under[1]:—

	1. Basalt, Bohemia. Unaltered.	Altered.	2. Greenstone, Cornwall[2]. Unaltered.	Altered.
Silica	44·4	42·5	51·4	44·5
Alumina	12·2	17·9	15·8	22·1
Lime	11·3	2·5	5·7	1·4
Magnesia	9·1	3·3	2·8	2·7
Potash...	0·8	0·2	1·6	1·2
Soda	2·7		3·9	1·7
Iron-protoxide ...	12·1	...	12·9	...
„ peroxide ..	3·5	11·5	2·5	17·6
Manganese-oxide	...	...	0·5	
Titanic acid ...	trace	1·2	0·7	1·0
Water	4·4	20·4	1·7	8·6
	100·5	99·5	99·5	100·8

Reduced to the same given proportions of alumina the relative proportions of the other substances in the same specimens are as follows:—

	1.		2.	
Alumina	100	100	100	100
Silica	364	237	325	201
Lime	93	14	36	6
Magnesia	76	19	17	12
Potash...	6	1	33	13
Soda	22			
Iron-protoxide ...	99	...	106	79
„ peroxide ...	29	64		
Manganese-oxide	...	...	3	
Water	36	114	11	38
	825	549	631	449

[1] 'Ann. des Mines,' 4 Ser., vol. vii. p. 37; vol. xii. p. 628.

[2] Mr. J. A. Phillips considers this rock to be an old dolerite. His analysis of it agrees closely with the above. Quart. Journ. Geol. Soc., vol. xxxiv. p. 472.

Thus showing that the loss caused by the decomposition of these rocks amounts in the total to,—

	1. *Basalt.*	2. *Greenstone.*
Silica ... ... Lime ... ... Magnesia ... ... Potash ... ... Soda ... ... Iron-oxides ... ... Manganese	44 per cent.	34 per cent.

The greater part of the iron-protoxide is also now present as a peroxide.

Serpentine in decomposing generally parts with a considerable portion of its magnesia and most of its alkalies.

It would thus appear that the greatest loss effected by decomposition in the igneous rocks is of the soluble alkalies; then follow in relative order the alkaline earths, the silica, and the iron. The silica passes off in greater part probably as a soluble silicate; and the earths, akalies, and metallic oxides as carbonates. They are first carried into the rivers and ultimately into the sea. There the lime, magnesia, silica, and iron are in greater part either precipitated by chemical reactions, or separated from the water by the action of living organisms—actions which, going on in all past geological periods, have led to the formation of the various limestones, oolites, and other calcareous strata of the sedimentary series, as well as to the deposits of diatomaceous earths and other accumulations of siliceous organisms.

The akalies, on the other hand, remain dissolved, except such small portions as are taken up by Algæ, or are retained in the insoluble residues by the remarkable absorbent power of alumina for these substances—especially potash—or have remained in the undecomposed portion of the felspars.

But, although the insoluble and soluble substances into which the decomposed silicates are resolved constitute so large a proportion of the original rocks, there is another portion which is not subject to decomposition, constituting from the first a mechanical residue, and which plays another very important part in the formation of the sedimentary strata.

Origin of Quartzose Sands and Sandstones. Granites consist, as before mentioned, of a more or less intimate mixture of quartz and felspar, in proportions varying, on the average, from 40 to 50 per cent. of each, with 5 to 10 per cent. of mica. The quartz forms a crystalline matrix, which, as the felspar decomposes, breaks up in fine-grained granites into grains generally of small size; or, if it be of coarser grain, then into larger fragments. As decomposition goes on the whole rock loses its coherence; and, on the removal of the decomposed soft parts, crumbles down into a grit or gravel of quartz, with flakes of the mica. These being comparatively indestructible, the only further change they undergo is through

wear, by which their angles are gradually rounded off, and the size of the grains reduced. This takes place on shore-lines, by tide and wave-action. The result is the production of a fine quartzose, and more or less micaceous sand, such as may be seen in the many beautiful small bays on the coast of the Land's End. All the soft and soluble ingredients of the decomposed silicates have disappeared, and a simple residue of micaceous quartzose sand, with some amorphous matter, remains. When, however, as not unfrequently happens, portions of the felspar resist decomposition, the sand becomes further mixed with a proportion of felspathic débris.

It is from this source that the materials of the various quartzose, micaceous, and felspathic sandstones of the sedimentary strata have been chiefly derived. Not that such strata are, as is also the case of the argillaceous strata, always derived directly from the crystalline rocks. On the contrary, they are constantly reconstructed by denudation from the earlier sedimentary strata of the same class. In these reconstructions, the only change which is effected is a greater amount of wear of the sand, and the gradual removal of all traces of felspar, which yields ultimately to the successive changes.

The extent to which sandstones were formed out of granitic débris during the Carboniferous and Triassic periods is very remarkable. Felspathic grains are common in many of the Coal-measure and Triassic sandstones; but as the sandstones are usually fine-grained, and the felspar much decomposed, their origin is not so immediately apparent. It is more evident in other strata. Some of the Millstone-grits of South Derbyshire are entirely composed of a quartz grit, with a very large proportion of rolled and worn grains of felspar; and Mr. Sorby [1] has shown from the microscopic examination of the Millstone-grit of South Yorkshire, that it would be difficult to find a better example of a coarse-grained sandstone almost entirely derived from granite. The felspathic sandstones of the Coal-measures of Central France consist in great part of granitic débris. In the small coal-field of Ahun especially, there are beds of micaceous sandstone containing all the elements of granite [2].

Near Angoulême a Jurassic sandstone contains so much decomposed felspar that it is worked and washed for China-clay. Several of the sandstones and argillaceous strata of the New Red Sandstone of Thuringia are worked for kaolin. One of these masses is seventy feet thick.

Extent of Disintegration. The decomposition of granite is not confined to the surface, but extends to considerable depths; and, as it is a feature of common occurrence, it constitutes an important factor in considering questions of denudation. It must be remembered, however, that the process of decay is very variable, depending on the nature of the felspar,

[1] Anniv. Address, Microscopical Soc. for 1877, p. 20.

[2] Explication de la Carte Géologique de France, vol. i. p. 642.

and upon climatic temperature and humidity. Thus, while the granite monuments of Egypt have remained unaltered for ages, the recent monuments of St. Petersburg already show symptoms of decay. Again, in this country, some of the Cornish granites (Lamorna, Penryn, etc.) furnish solid and enduring materials for our public monuments, while others (St. Austell, etc.) are so decomposed as to form a mass of quartz grit and white clay (kaolin), that can be readily removed with pickaxe and spade.

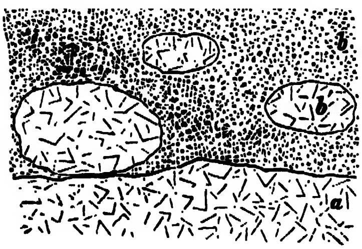


FIG. 14.—Section of a decomposed surface of granite. *b*. Decomposed granite, forming *in situ* an irregular loose grit or gravel of quartz fragments, with some clay and mica; *b'*. blocks of hard undecomposed granite; *a*. the solid unaltered granite.

Granite. Over large tracts in Cornwall, France, Spain, India, Central Asia, and elsewhere, the granite is so disintegrated that the country presents a surface of fine quartz grit or gravel, while the granite of the Alps, of Aberdeen, and many other places, is subject to little change. The depth to which decomposition extends is very variable; sometimes to a few feet, at others to more than a hundred feet. The decay is also irregular, some parts of the same granite resisting decomposition more than others.


FIG. 15.—*View of the Hay Tor Rocks, Devonshire* (from a sketch of Dr. Buckland's).

At the Carclaze Mine near St. Austell, the granite, which is well exposed in a deep open section, is decayed and rotten to the depth of 80 to 100 feet. In Auvergne, there are granites which have decomposed to the depth of more than 100 feet, and the alteration is said to extend still deeper in Brazil and other places.

In the section, Fig. 14, are blocks (*b'*) which remain intact in the midst of the decomposed mass. This has arisen from some difference in crystal-

lisation or in composition, which has rendered portions of the granite more indestructible than others. These resisting centres give rise to one of the most peculiar features of a granitic district; for, wherever the denuding forces have been sufficient to remove the grit (*b*), but insufficient to remove the blocks (*b′*), the ground is strewed with the granite boulders (mistaken sometimes for erratic blocks), or with successive superimposed blocks (Fig. 14), left in place. It is to this cause that are due the many isolated 'Tors' so characteristic of the scenery of Dartmoor, the Land's End, and other granite districts.

The same cause affects granitic cliffs, rounding the surfaces formed by the 'joints,' and often leaving detached blocks on the brow of the cliff; and they also give rise to the Rocking Stones common in granite districts.

From the same cause, but on a large scale, the contours of prominent heights have become rounded, and many granitic hills have assumed the soft and undulating outlines of our chalk-downs.

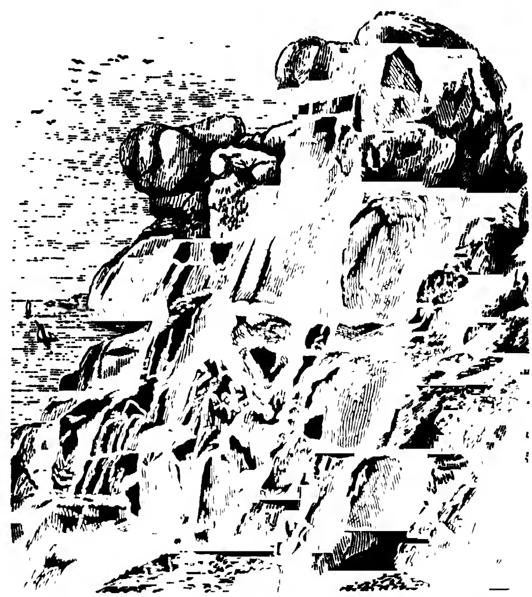


FIG. 16.—*View near the Land's End* (from a photograph).

This alteration of granite proceeds often with comparative rapidity. In drift beds of quaternary age, while the fragments of sandstone and limestone are unaltered, the harder granite pebbles are sometimes thoroughly disintegrated, and will fall into fragments when removed. There may often be seen in the neighbourhood of granitic districts small boulders lying at the depth of several (8 to 12) feet in permeable valley- and drift-gravels, and therefore removed from any material alternation of temperature, but subject to the percolation of water, thus disintegrated and softened. The case of the monuments of St. Petersburg has been already alluded to; but there the influence of cold constitutes an important element in the change. Another illustration of the rapid rate of decay was furnished by the discovery a few years since in the south of France of some Roman mill-stones of granite buried in a heap of débris, and which were found to be converted throughout into a kaolinised grit. Moisture, or even a damp condition, is the great element in effecting the decomposition of granite.

The mica-less granite, pegmatite, is very liable to decompose. At Itsasson, near Bayonne, this rock is decayed to a depth exceeding 150 feet,

FIG. 17.—*View of the Granite Mountains north of La Corrèze* (after Dufresnoy). *The five birds are to show the position of Ussel.*

and horizontally on the side of the hill for a distance of more than 100 feet. It forms a very fine white kaolin with free quartz.

Some gneisses are also extensively decomposed, forming kaolin clays more or less pure; this is of common occurrence in Auvergne and other parts of Central France. Around Rio Janeiro the gneiss has decomposed into a reddish clay, from a few inches to 100 feet deep. In the Pyrenées the disintegration extends to depths of 40 to 50 feet, or more.

FIG. 18. *Section of a decomposed Gneiss and an unaltered metamorphic Limestone near Itsasson* (Basses Pyrénées).

Professor Ansted describes[1] the syenites and diorites in Guernsey and Jersey 50 feet or more; and he states that a considerable part of the north of the island of Alderney consists of a thick bed of sand and fine gravel with boulders, the whole mass being derived from the decomposition of the greenstone rock *in situ.*

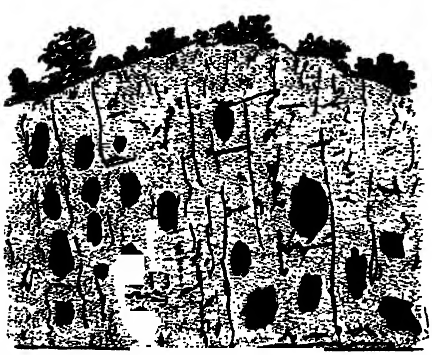


FIG. 19. *Section of decomposed Ophite on the railway south of Bayonne.*

Other Rocks. The ophite (diorite) of the Pyrenees is disintegrated generally into a bright brown argillaceous mass with concentric nodules or sub-angular blocks of the unaltered rock remaining *in situ*, and to such a depth that the unaltered rock rarely shows in the pits or railway-sections which are 30 to 40 feet deep. This is of late Cretaceous and Miocene age.

[1] On Some Phenomena of the Weathering of Rocks, Trans. Cambridge Phil. Soc., vol. xi.

Serpentine is sometimes decomposed to a considerable depth. This is frequent in Northern Italy. In addition to the formation of unctuous clays, the change sets free carbonate of magnesia and silica, which are deposited in veins traversing the altered rock.

Basaltic rocks are decomposed often to great depths, and generally give rise to impure ferruginous clay, although at times the iron has been so far removed as to leave a light-coloured clay. The grains of titaniferous iron which may be present remain unaltered.

Laterite and Palagonite, which are rocks in places of considerable local importance, are merely weathered and altered forms of lava, often scoriaceous and tufaceous, in which the protoxide of iron has been changed into the peroxide, and the rock has assumed various bright colours of red and yellow, and of brown passing to black.

The schistose rocks are also subject to change. A talcose schist in the neighbourhood of Pau and Bagnères is so altered that the disintegrated mass is worked as a marl for manure. Other schistose rocks have been found to pass into an impure fuller's earth.

Thus, all the constituents of the sedimentary rocks can be traced back to decomposed igneous rocks;—the indestructible quartz, with mica, or rarely talc, forming the base of the sandstones; the elements of the various silicates reappearing in other and altered forms, the felspars changed into insoluble kaolins, the basis of all clays; the earths, having combined with carbonic acid, form calcareous strata; and the liberated silica falling as a precipitate, or becoming subject to further change by acidified water or by organic matter. Besides freeing these earths and alkalies, other silicates have liberated iron and manganese oxides, together with the titanic, phosphoric, and fluoric acids, which latter combined with lime and other bases are so widely though sparsely dispersed in sedimentary strata. The alkalies, on the other hand, are for the greater part permanently freed as soluble carbonates and chlorides[1].

Secondary Products. Besides these direct products, a number of secondary ones are formed as the result of subsequent reactions. Amongst the most common are certain sulphates, some oxides, and various carbon compounds,—many of the changes being due to the action of organic matter on metallic oxides and sulphides.

The decomposition of some plutonic rocks enclosing mineral segregations, and especially of mineral veins (Chapter XIX) with their metallic sulphides, must, by the oxidisation of the latter, have always supplied the surface-waters with a proportion of sulphates. The most readily formed

[1] Since this chapter was written, an interesting paper 'On the Decay of Rocks' has been published by Dr. Sterry Hunt in the Amer. Journ. of Science, vol. xxvi. p. 190, Sept. 1883, which the reader should consult.

of these—the sulphate of iron—carried down, and fixed with the argillaceous sediments resulting from the conjoint rock-decomposition, becomes exposed to the reactions of the carbonates of the earths and alkalies present in all clays. One of these reactions would be the production of sulphate of lime (gypsum and selenite), and of carbonate of iron,—the latter often passing into a per-oxide; while the sulphate of lime has segregated out and forms the crystals of selenite so common in many clays [1]. Should, however, as is so frequently the case, organic matter be present, then the sulphate of iron may be de-oxidised and reduced back to the sulphide, which either remains in an impalpable state diffused through the clay, or, when both substances are present in larger quantities, the production of iron-sulphide is effected on a larger scale, and results in the segregation of nodules or layers of iron-pyrites, or by its replacing and fossilising the substance of the contemporary organic remains, a condition so frequent in the London, Oxford, and other clays. These secondary products will be more fully considered in Chapter VII.

Importance in Questions of Denudation and Time. The importance of this process of rock-decay on questions of denudation and time has not hitherto received sufficient consideration; and yet it cannot be too strongly insisted upon. It is clear that all sedimentary strata have been derived from the destruction of pre-existing rocks; and all the estimates of geological time required for the accumulation of these strata have been based on the denudation of the land as now effected. At present the wear of land-surfaces is on the whole very slow, being almost entirely mechanical, and only chemical in the case of calcareous rocks. The rivers carry down the loam, clay, and sand, and the loose fragments of the comparatively indestructible rocks forming the great bulk of the existing lands; or the sea pounding on the coast, breaks up and distributes similar débris.

The sedimentary strata which consist of the débris of older surfaces, being altogether derivative, it is evident that, as we go back in geological time, their extent was less and less, and that with the progress of time, first, portions of the original surface of the globe, and then, in succession as formed, the Archæan and Palæozoic rocks, have been covered up and hidden under successive sedimentary strata. Consequently, there was a time when the whole surface consisted of some form of crystalline or igneous rocks—rocks subject even in our present atmosphere to much decomposition, and doubtlessly in the atmosphere of past times to a decomposition far more rapid; and these rocks, always subject to decay and alteration of texture, must have yielded to wear and removal with a facility unknown amongst mechanically formed and detrital strata where erosion alone operates. The

[1] This, of course, is only an exceptional mode of formation. The ordinary sedimentation of gypsum is effected in very different ways, such as evaporation of sea-water, &c.

entire area of the original crust, the extensive areas of the Archæan rocks, and the widely spread extrusive rocks of Palæozoic times, furnished materials subject to constant change and decay—a decay probably not regular and uniform, but, like that of granite and basalt at the present day, affecting some parts more than others. Is it not even possible that the old surfaces of these rocks in Palæozoic and later times may represent only the harder cores and more indestructible portions of original masses of greater extent, and of which the decayed and less resisting portions have been removed and lost?

We have, therefore, in this early condition of the land-surfaces, a reason why degradation and denudation should have proceeded with much more rapid strides than at present, and one reason also why, as a consequence of the abundance of materials, the earlier formations were built up of such large dimensions and thickness, and further why the dimensions of the strata on the whole decrease in volume from the earlier to the present times. This may not be the sole reason, but it is a factor equally important with that of time.

All the calculations therefore of the length of geological time based upon the evidence furnished by denudation as now known, seem to me to be fallacious, and to have led to serious error in assigning to that time the unlimited length which, based on data applicable only to parts of the case, has, in dealing with this question in its relation to the antiquity of the globe, led to such measures being assumed to be applicable to the whole term.

CHAPTER V.

ORDER, PLACE, AND RANGE OF PAST LIFE.

OBJECTS OF THE CHAPTER. CLASSIFICATION PREFERRED. DISTRIBUTION OF EXISTING AND EXTINCT FORMS IN SYSTEMATIC ORDER AND IN GEOLOGICAL TIME—FIRST, PLANTS; SECONDLY, THE INVERTEBRATA: PROTOZOA, CŒLENTERATA, ANNULOIDA, ANNULOSA, MOLLUSCA; THIRDLY, THE VERTEBRATA: FISHES, AMPHIBIANS, REPTILES, BIRDS, MAMMALS.

HAVING described the nature of the inorganic substances entering into the composition of the earth's crust, and the chemical changes to which they are subject, it now remains to give an outline of the classes and orders under which the various forms of life existing at the different geological periods on the earth's surface have been grouped by naturalists. My object will be merely to give such a general sketch or lists of the orders and families of the vegetable and animal kingdoms as may serve to show the relation which the life of former geological periods bears to that of the present, or its position in regard thereto, and the relative importance and place in nature of the various forms of this past life.

Classification preferred. While to the biologist and palæontologist belongs the determination of the structure of the fossil and its relation to other analogous forms of life, to the geologist belongs the determination of its exact position in geological time, and of its surroundings and associations. To both its position in the geological record, and its relation to the preceding and succeeding forms of life, are matters of common interest requiring constant co-operation.

The palæontologist is, however, restricted not only to remains of the harder parts, or skeletons of the fossil animals, but too often to mere fragmentary portions; the softer parts of the animal needed by the biologist to determine its organs and affinities, so essential to a natural classification, have, with a few rare exceptions, perished in the process of fossilisation. Consequently, an arrangement more artificial and which enables him to assign it, even as a preliminary step, a place in natural order is, for the present at all events, the more convenient one to the geologist. For example, Agassiz's classification of the fossil fishes, based mainly on their teeth,

scales, and spines, presents, in many respects, a certain convenience over the more perfect symmetrical classifications now adopted by naturalists for living fishes.

In like manner, it is indispensable to the botanist to have the flowers and seeds of the plants he seeks to classify; but these parts of the plant are very rarely accessible to the palæophytologist, who has to rely on the external form—more rarely on the internal structure of the wood—and on the shape and venation of the leaves, these being the characters which too generally constitute his only available evidence.

It is, therefore, often expedient for the palæontologist and geologist, who have to work upon a different base and with imperfect data, to adopt at times a standard somewhat different from that of the professed naturalist and biologist. It is also to be observed that a grouping which deals rather with the mode of life and with the part filled by the animal in the economy of nature, is the one which best serves the generalisations of the geologist; for example, the division of the extinct saurians into those of marine habits (Enaliosauria, etc.) and those of land habits (Dinosauria, etc.), and of the univalve mollusca into those which are carnivorous and those which are vegetable-feeders, are specialised characters of peculiar significance to the geologist.

System and Distribution in Time. The order of succession to be preferred is the ordinary one, which proceeds from the more simple to the more highly organised classes. For, whatever may have been the perfection of some forms at early geological periods, it will be evident that the more perfect classes, both of the vegetable and of the animal kingdom, gradually succeed during later periods.

Organic matter is linked on to the inorganic through forms of infinitely simple structure. Vegetable life first assimilates carbonic acid and moisture from the air or water, and converts these inorganic substances into organic vegetable tissue, which, in its turn, serves to feed that animal life which has not the power to assimilate directly the inorganic matter itself. However low, therefore, the form of animal life, we may presume it was preceded by some form of vegetable life, although from the convertibility of plant-remains under certain conditions into some amorphous form of carbon, the geological evidence of their existence is not always forthcoming; or rather, the metamorphism of the older rocks has rendered the evidence obscure by reducing the plants to the state of graphite or other altered forms of carbon.

In the following tabular lists,—which are intended merely to enable the reader to distinguish the extinct fossil from the recent forms of life, and their relative places in nature,—the orders and families (or genera where given) which are both living and extinct are printed in *ordinary* *e*, while those of which there are extinct forms only are in *italics*, and

those of which there are only living forms are in small *capitals*. It will be observed that by far the larger proportion of all classes of the vegetable and animal kingdoms are represented in a fossil state, and that those which are altogether absent consist chiefly of those soft and gelatinous animals which afford no hard parts for preservation, and which may have existed, though they have not been preserved. It must, however, be borne in mind, that, whereas in present nature we see only one horizon, we are looking back in this summary through many successive horizons of the past. The relation of those several horizons one to the other will be shown in the chapters on Stratigraphical Geology, where the life existing at each of the many geological epochs will be specified separately.

PLANTS.

The organs of plants are built up of cellular, vascular, and fibro-vascular tissue; the Thallogens consisting of cellular tissue alone; while vascular tissue is confined to the other section of Cryptogamic plants—the Acrogens, and to the Phanerogamic plants. The vegetable kingdom is divided into two groups,—the first consisting of plants having no distinct flowers or proper fruit; and the second of plants having distinct flowers and seeds.

				EXAMPLES OF FOSSIL GENERA.
1. Cryptogamic or Flowerless Plants	Thallogens		Algæ (Sea-weeds, Diatoms, etc.)...	*Chondrites*, *Buthotrephis*, *Eophytum*, *Caulerpites*, *Chara*, etc.
			Fungi	*Archagaricon*, *Xylomites*, Sphæria.
			Lichens ...	Cladonia, *Cornicularia*.
	Acrogens		Mosses	Hypnaceæ (?).
			Lycopodiaceæ (Club-mosses)	*Lepidodendron*, *Sigillaria*, *Knorria*.
			Equisetaceæ (Horsetails)...	*Calamites*, *Annularia*.
			Filices (Ferns)	*Pecopteris*, *Neuropteris*, *Caulopteris*.
2. Phanerogamic or Flowering Plants	Gymnosperms ...		Conifers... ...	*Dadoxylon*, *Pinites*, *Walchia*, Sequoia, Thuya, Abies, Taxodium, etc.
			Cycads	*Zamites*, *Pterophyllum*, *Næggerathia*.
	Angiosperms	Endogens or Monocotyledonous plants	Grasses	Phragmites.
			Lilies	Yuccites.
			Palms	*Flabellaria*, *Pothocites*, Chamærops.
		Exogens or Dicotyledonous plants	Ordinary trees and plants—Oak, Ash, Crab, etc. ...	*Hightea*, *Faboidea*, *Credneria*, Quercus, Ficus, Platanus, Populus, Betula, Rhamnus, etc.

Almost all existing families of plants have their representatives in a fossil state, although their distribution in past periods has differed widely from that now prevailing.

The cellular Cryptogams, represented by some Sea-weeds, appear in the Lower Palæozoic series. Vascular cryptogams, represented by *lycopodiaceous* plants (Club-mosses), together with ferns, make their first appearance in the Silurian strata, and these, later on, constitute the dominant vegetation of the Palæozoic series.

Phanerogamic plants. The *Gymnosperms,*—which include the Conifers, such for example as the yew and spruce,—commence with a few orders in the Middle-palæozoic, and continue through the Secondary and Tertiary periods up to the present time. The Cycads commence in the Palæozoic, and form the most characteristic plants of the Secondary series, where they abound.

Of the *Angiosperms*, a few, belonging to the *Endogens* or *Monocotyledons*, appear in the Carboniferous period; they become more abundant in the Jurassic period, and have now attained their maximum development.

The *Dicotyledons*, or the existing common deciduous trees, did not exist in the Palæozoic period; they are only faintly represented in the Lower Secondary strata; they are fairly numerous in the Upper Secondary, and become the dominant vegetation in the Tertiary period, as they are of the present time.

In addition to these, there are the microscopic **Diatoms,** a low order of vegetable organisms, living in salt and fresh-water, and having a siliceous framework, which, notwithstanding their excessive minuteness, form deposits of considerable extent of Tertiary and Quaternary date; and are not wanting in the older Formations.

THE INVERTEBRATE ANIMALS.

Of these there are five divisions.

I. **PROTOZOA.** The first or lowest division of the animal kingdom consists of those animals the body of which is composed of a jelly-like albuminous substance, called sarcode, or tissues composed of definite cells. Two of the classes of protozoa are not found fossil.

1. GREGARINIDÆ.
2. Rhizopoda ... ... { Foraminifera,—Miliolida, Lagenida, Textularida, Globigerinida, and *Nummulitidæ*. Radiolaria,—Thalassicollidæ, Polycystinidæ.
3. INFUSORIA.

Foraminifera make their appearance in the earliest of the geological series, the *Eozoön Canadense* being found in the Laurentian strata. Various foraminifera are found in the Silurian rocks, as well as in the Carboniferous limestone. In the Secondary rocks they occur in great abundance; but they attain their maximum development in the Tertiary period, occurring

in great profusion in some Eocene strata, and are equally abundant now[1]. **Radiolaria** appear in Mesozoic and abound in Tertiary times.

II. **THE CŒLENTERATA**, which include the Corals, are very important in their geological relations. Their structure is rather more complex, or higher, than that of the Protozoa; but still they have no blood vascular system. The organs round the mouth are arranged in a star-like or radiated form. Traces or impresses of jelly-fishes and sea-anemones are very rarely preserved in a fossil state. The Cœlenterata are divided into four classes.

	SUB-CLASS AND ORDER.		FAMILIES AND GENERA.
1. Spongia	Spongidæ: Siphonidæ, *Ventriculidæ*.		
2. Hydrozoa	Hydroida	Corynida Hydraticina.	*Palæocoryne*.
	Graptolitidæ		
	Hydrocorallinæ	Milleporidæ.	
3. Actinozoa (Anthozoa; Corals) ...	Zoantharia malacodermata ...	Sea-Anemonies.	
	„ sclerobasica ...	Antipathes.	
	„ sclerodermata (stony corals)	Tabulata[2] (with tabulæ)... ...	*Favositidæ, Halysitidæ*,
	„ (corals having septa in multiples of six)	Perforata (without tabulæ) ...	Eupsamidæ, Poritidæ, Madreporidæ.
		Aporosa (without tabulæ) ...	Fungidæ, Astræidæ, Oculinidæ, *Turbinolidæ*.
		Tubulosa	*Auloporidæ*.
	Rugosa (corals with septa in multiples of four)	*Stauridæ*	*Cyathaxonidæ*.
		Cyathophyllidæ	*Cystiphyllidæ*.
	Alcyonaria (corals not divided by septa)	Tubiporidæ ...	Pennatulidæ.
		Gorgonidæ ...	Rhipidogorgia.
4. Ctenophora.	Medusæ.		

Sponges also make their appearance in early Palæozoic strata (Cambrian), and attain their maximum development in the Cretaceous period. The flints which form so characteristic a feature in the white Chalk of England have originated in greater part in siliceous segregations on sponges[3].

Some of the orders belonging to the Hydrozoa, such as the **Graptolites** which possessed a horny or chitinous texture, have been preserved in great numbers in early Palæozoic times; whilst the Stony **Corals** contribute largely to the organic remains of all geological periods. The coral-animal itself resembles a sea-anemone; but while, owing to the absence of any framework or skeleton in the latter, its remains are never

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[1] For the range of Foraminifera in time, see Prof. Rupert Jones in 'Proc. Geol. Assoc.,' vol. ii. No. 4, 1873, and his 'Cat. Foss. Foraminifera,' Brit. Mus. 1882.

[2] This separate division is now abolished by the best authorities since the Corals with *tabulæ* are not otherwise related. It is however a convenient division for a large group of peculiar extinct forms.

[3] For their distribution, see Hinde's 'Fossil Sponges.'

preserved[1], the framework of the former is amongst the commonest of fossils. Certain genera and species inhabit deep water, while others are confined to shallow waters and are reef-builders. The chief genera of the former group are Caryophyllia, Balanophyllia, and Dendrophyllia. They are mostly single separate corals, and are generally small, though a few attain a considerable size. The great majority of the 'reef-builders,' on the contrary, are massive compound or branching corals, such as Madrepora, Porites, Astrea, etc., and often attain a large size.

Corals first appear in the Lower Silurian, and abound in the Upper Silurian strata and in the Devonian and Carboniferous limestones. The Rugosa are confined to Palæozoic strata. In the Jurassic strata corals are also very abundant; the 'Coral-rag' owes its name to the prevalence of this class of fossils. They are again numerous in the Tertiary period; but it is not until the present period that they reach their greatest development[2].

III. **THE ECHINODERMATA.** This division consists of animals with a radial arrangement and with a skin bearing spicules and indurated by calcareous deposits. They possess a digestive canal and a true vascular system.

ORDER.	FAMILY.	ORDER.	FAMILY.
Echinoidea (Sea-urchins)	*Ananchitydæ.*	Crinoidea (Stone-lilies)	Comatulidæ.
	Cassidulidæ.		*Apiocrinidæ.*
	Echinidæ.		*Cyathocrinidæ.*
	Clypeasteridæ.		*Cupressocrinidæ.*
	Spatangidæ.		*Marsupitidæ.*
	Cidaridæ.		Pentacrinidæ.
	Galeritidæ		*Melocrinidæ.*
	Perischoechinidæ.		*Polycrinidæ.*
Asteroidea (Star-fishes)	Asteridæ.	*Cystoidea*	*Cystidæ.*
	Crenasteridæ	*Blastoidea*	*Pentremitidæ.*
	Ophiuridæ.	HOLOTHURIOIDEA ...	(Sea-cucumbers.)

With the exception of one extinct family of **Echinodea**—the Perischœchinidæ, which is exclusively Palæozoic—the other families of this order come in with or after the Trias, abounding especially in later Mesozoic times, and continuing to the present day.

The **Asteroidea** are first known in the Lower Silurian strata, abound in the Jurassic series, are common in the Cretaceous, comparatively rare in the Tertiary series, and are again common at the present period.

The **Ophiuroidea** appear in the Silurian series, are common in the Mesozoic period, and now show a decrease.

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[1] It is reported, however, that some impressions referable to this order have recently been discovered in Sweden.

[2] See Prof. P. Martin Duncan's 'Reports on Brit. Foss. Corals in Proc. Brit. Assoc.' for 1868, *et seq.*

The **Crinoidea** are found early in the Cambrian strata, and attain their maximum in the Upper Palæozoic series, where they are represented by a number of extinct families. In the Secondary period, Crinoids, though still abundant, become less numerous. In the Tertiary period Crinoids were reduced to three families, and the five living families are widely though irregularly distributed [1].

The **Cystoidea** and **Blastoidea** are not only extinct, but they are entirely confined to Palæozoic strata.

VERMES. The large class of Worms is, with the exception of the Annelids, of no geological importance, as none of the Scolecidæ have been found in a fossil state.

	Orders and Families.	Fossil Genera.
Annelida	Abranchiata	*Nemertites.*
	Dorsibranchiata	*Nereites, Arenicolites.*
	Tubicola	Serpula, Vermilia.

The **Annelids** are amongst the oldest of known fossils. They are familiar to us in the present day in the small Serpulæ; but in the Silurian series the shelly forms of this family are found more than a foot in length. Annelids also form borings and worm-like tracks in some of the Silurian rocks, where hardly any other trace of life has been preserved. The representatives of this group, which never becomes important, continue to the present day.

IV. **ARTHROPODA.** The animals of this division have a nervous and circulatory system, and a body divided into segments. They form four groups.

	Orders and Families.		Fossil Genera.
1. Entomostracous Crustacea	Cirripedia	Balanidæ	(Acorn shells). Balanus.
		Lepadidæ	(Barnacles). Pollicipes.
	COPEPODA.		
	Ostracoda	Cyprididæ	*Cypris, Candona, Bairdia.*
		Cytheridæ	*Cythere, Cythereis, Cytheridea.*
		Cypridinidæ	*Cypridina.*
		Leperditoidæ	*Leperditia, Beyrichia.*
	CLADOCERA.		
	Phyllopoda		*Hymenocaris,* Estheria, *Ceratiocaris, Aptychopsis.*
	Eurypteridæ		*Eurypterus, Pterygotus.*
	Xiphosura		*Bellinurus, Prestwichia,* Limulus.
2. Malacostracous Crustacea	Amphipoda		(Sand-hoppers). Prosoponiscus.
	Trilobita		*Paradoxidæ, Phacopidæ, Asaphidæ,* etc.
	Isopoda		(Wood-lice). *Præarcturus, Archæoniscus.*
	Stomapoda		(Locust-shrimps), *Palæocaris,* Squilla.
	Decapoda	Macrura	(Lobsters). *Glyphea.*
		Anomura	(Hermit-crabs). *Pagurus.*
		Brachyura	(Crabs), *Zanthopsis.*

[1] See Morris, 'On the Geol. Distribution of Fossils,' Proc. Geol. Assoc. for 1877, for these and other forms.

	ORDERS AND FAMILIES.	GENERA.
3. Arachnida and Myriapoda ...	... ...	(Spiders, Scorpions, Centipedes). *Eoscorpius, Eophrynus, Xylobius.*
4. Insecta	Hymenoptera	(Bees, Ants, etc.)
	Neuroptera	(Dragon-flies, etc.). *Dictyoneura.*
	Orthoptera	(Crickets, Grasshoppers, &c.), *Blattina.*
	Coleoptera	(Beetles). Curculionidæ.
	Hemiptera	(Bugs, Aphides).
	Diptera	(Flies, Gnats).
	Lepidoptera	(Butterflies, Moths). *Palæontina.*

Owing to the aquatic habits of the **Crustacea,** and to the calcareous or horny nature of their casing, they have left their remains in all the sedimentary strata. They commence early in the Cambrian period, and certain forms—such as the Trilobites—are abundant in, and characterise many of the Palæozoic strata, beyond which they do not extend[1].

The King-crab family (Limulidae) appear in Upper Silurian strata; several species are met with in the Coal-measures; they range through the Oolites, and are found now living.

Of the order Decapoda, which includes the higher forms of the Crustaceans, such as the lobsters and crabs, some examples have been found in the Carboniferous rocks; but it is in the Jurassic and Cretaceous strata that these Crustaceans become abundant. In the London-clay crabs are very numerous, as they are also at the present day.

Myriopoda commence in Silurian, and the Arachnida in Carboniferous times.

Other families make their appearance later, such as the **Balanidæ,** which, with the exception of one doubtful genus, commence in Lower Tertiary strata; and the **Lepadidæ,** which, with one exceptional Silurian genus, commence in the Trias, and range up to the present time.

The **Entomostraca** range from the Lower Cambrian to the present day. One family of minute bivalved crustaceans, the Cyprididæ, swarm in some fresh-water (*Cypris*) and some marine (*Bairdia*) deposits. They are commonly known as Water-fleas; and these, although so small, have sometimes accumulated to such an extent as to produce a lamination in the beds in which they occur, and add to the mass of others, thus having considerable geological importance.

Insects are poorly represented in the geological record: a few remains of them are found in the Devonian and Carboniferous rocks, and many remarkable specimens have been met with in the Secondary and Tertiary series; although there are often indications of their having

[1] See Dr. H. Woodward's 'Cat. Brit. Foss. Crustacea,' 1877.

abounded, yet, owing to the facility with which insects disintegrate, their remains are rarely preserved.

V. The **MOLLUSCA** are soft-bodied animals, usually protected by a univalve or bivalve shell consisting almost entirely of carbonate of lime[1]. The Bivalve Mollusca are acephalous, *i.e.* destitute of any distinct head; and they are all aquatic. The univalves inhabit water and land, and are all furnished with a distinct head, as are also the Cephalopoda, which have powerful jaws like the mandibles of birds. The *Molluscoida* are a sub-class of special organisation, enclosed by a cell or by a bivalve shell.

	CLASS.		FAMILY.
Molluscoida.	1. Polyzoa (or Bryozoa).	Fixed to some object...	*Fenestellidæ*, *Myriaporidæ*, Escharidæ.
	2. Brachiopoda. (Attached shells.)	Hinges articulated ...	Terebratulidæ, *Spiriferidæ*, Rhynchonellidæ. *Strophomenidæ*, *Productidæ*, Thecididæ.
		Hinges not articulated	Craniadæ, Discinidæ, Lingulidæ.

(Mollusca proper).			
1. Lamellibranchiata (Conchifera). Bivalve shells.	Monomyaria. (Shells with one muscular impression.)	Ostræidæ	Asiphonida, or shells with no respiratory syphon; non-burrowers.
		Pectinidæ	
		Aviculidæ	
		Limidæ	
	Dimyaria. (Shells with two muscular impressions.)	Mytilidæ	
		Arcadæ	
		Trigoniadæ	
		Unionidæ	Siphonida, or shells with respiratory syphons. Most of these burrow in sand and mud.
		Chamidæ	
		Hippuritidæ	
		Tridacnidæ...	
		Cardiadæ	
		Lucinidæ	
		Cycladidæ	
		Cyrenidæ	
		Cyprinidæ	
		Veneridæ	
		Mactridæ	
		Tellinidæ	
		Solenidæ	
		Myacidæ	
		Anatinidæ	
		Gastrochænidæ	Burrowers in mud, stone, or wood.
		Pholadidæ	

[1] The following is the composition of two common recent shells:—

	Oyster.	*Venus.*
Carbonate of lime	93·9	96·6
„ magnesia	0·3	trace
Sulphate of lime	1·4	0·3
Phosphate of lime	0·5	0·1
Organic matter	3·9	3·0
	100·0	100·0

CLASS.		FAMILY.	
2. Gasteropoda. Univalve shells.	Siphonostomata. (Shells with a groove or notch at the end of the aperture to give passage to a syphon.)	Strombidæ	These families are flesh-feeders or carnivorous (zoophagous).
		Muricidæ	
		Buccinidæ	
		Conidæ	
		Volutidæ	
		Cypræidæ	
	Holostomata. (Shells having no syphon; aperture entire or unbroken.)	Naticidæ *	Excepting those marked with an asterisk, this group are all vegetable-feeders (phytophagous).
		Pyramidellidæ *	
		Cerithiadæ	
		Melaniadæ	
		Turritellidæ	
		Litorinidæ	
		Paludinidæ	
		Neritidæ	
		Turbinidæ	
		Haliotidæ	
		Fissurellidæ	
		Calyptræidæ	
		Patellidæ	
		Dentaliadæ *	
	(Body covered by plates.)	Chitonidæ	Corneous covering.
	Tectibranchiata. (Shell rudimentary or wanting.)	Tornatellidæ	Chiefly animal-feeders.
		Bullidæ	
		APLYSIADÆ	
		Pleurobranchidæ ...	
		PHYLLIDIADÆ	
	Nudibranchiata. (Destitute of a shell, except in an embryo state.)	DORIDÆ	Sea-slugs and Sea-lemons.
		TRITONIADÆ	
		ÆOLIDÆ	
		PHYLLIRHOIDÆ ...	
		ELYSIADÆ	
	Pulmonifera. (Air-breathers.)	Helicidæ	Without opercula to the aperture.
		Limacidæ	
		ONCIDIADÆ	
		Limnæidæ	
		Auriculidæ	
		Cyclostomidæ	
		ACICULIDÆ	
3. Pteropoda.	Very thin and fragile shells.	Hyaleidæ	Univalve shells, living only in the open sea.
		Limacinidæ	
		CLIIDÆ	
4. Heteropoda or Nucleobranchiata.	Discoidal shells, not chambered. Swimmers in open ocean.	Firolidæ	Only one fossil species.
		Atlantidæ	Mostly all fossil genera.
5. Cephalopoda.	Tetrabranchiata. (Shell external, chambered.)	Nautilidæ	The species of this class are all marine and carnivorous
		Orthoceratidæ	
		Ammonitidæ	
	Dibranchiata. (Shell internal, Argonaut excepted.)	Argonautidæ	
		OCTOPODIDÆ	
		Teuthiadæ	
		Belemnitidæ	
		Sepiadæ	
		SPIRULIDÆ	

The ordinary Mollusca hold a most prominent rank amongst fossils; for, owing to the hard texture of their calcareous coverings, they furnish more than one half the species of the British organic remains—7416 out of 13276.

The lowest class, the **Polyzoa** (or Bryozoa), commence in the Upper Cambrian, and are well represented in the other Palæozoic rocks. In the Secondary period they are common; but they attain their maximum development in the Cretaceous period. They are again abundant in the Crag.

Brachiopoda are *equilateral* and *inequivalved* bivalve shells, attached to rocks, wood, or sea-weed by means of a peduncle passing through the beak, or by direct fusion of the ventral valve with the rock; they are amongst the most numerous and characteristic shells of the Palæozoic series; the Spiriferidæ, Rhynchonellidæ and others having abounded in Silurian, Devonian, and Carboniferous times. The Terebratulidæ, on the other hand, commenced later (Devonian), and attaining a maximum development in the Cretaceous period, are still common in some seas. One genus of Brachiopods, a small Lingulidid, ranges through all time, being present in the Cambrian rocks and living in the existing seas.

The Lamellibranchiata, or ordinary (*inequilateral*) bivalve shells, first appear sparingly in the Silurian strata, become very numerous in the Mesozoic strata, and attain their maximum in the present day.

The Gasteropoda, or univalves, have also a very wide distribution in time, ranging from the Upper Cambrian rocks, increasing less rapidly than the Bivalves, and, like them, attaining their maximum development at the present day.

With one exception all the Lamellibranchs and the Gasteropods belong to living families, and a large proportion to living genera.

The **Pteropoda,** all now of small size, are swimmers on the surface of the open ocean, where they often occur in enormous numbers: they commence in the Lower Silurian, and soon become numerous, but a large proportion of the genera die out in the Palæozoic period. They afterwards become much scarcer, and comparatively few genera exist at the present day, but the individual species occur in large numbers.

The Heteropoda are also free swimmers on or near the surface of the open ocean. The Atlantidæ is represented in the present day by one genus only (Atlanta). The important fossil genus of Bellerophon, which ranges from the Upper Silurian to the Carboniferous series, is now considered to be more closely allied to Pleurotomaria. Other Palæozoic genera are Maclurea and Cyrtolites.

Cephalopoda. This class of the Mollusca includes the most highly organised orders, such as the Cuttlefishes, Nautili, Ammonites, etc. They are largely represented in the Palæozoic and Mesozoic series. The

Tetrabranchiate section ranges from the Lower Silurian, and dwindles down to the present day, most of the families and genera having died out and have not been replaced by others. The Ammonitidæ, which commence in the Silurian series (in Bohemia), entirely died out by the end of the Cretaceous series; while the Nautilidæ, which also made their first appearance in the same series, though decreasing in numbers to the present day, are still represented by a living genus.

No dibranchiate Cephalopod is supposed to have existed in Palæozoic times: but they abounded in the Mesozoic period. The Belemnitidæ which, like the Sepia, had an internal shell—the part usually found fossil—are exclusively Mesozoic, commencing in the Lias, and continuing to the end of the Cretaceous period, when they died out. Other families of this section, however, still exist [1].

THE VERTEBRATE ANIMALS.

These are divided into five classes.

I. FISHES are vertebrates provided with gills or branchiæ, by means of which they abstract air from the water, in which medium this provision fits them to live. Omitting the small sub-class of Marsipobranchii, of which there are no traces in a fossil state, the other fishes are divided into three great groups: 1st, Those with cartilaginous skeletons and without scales—the Elasmobranchs; 2nd, Those with skeletons either bony or cartilaginous and body covered with bright bony plates or scales—the Ganoids; 3rd, The common bony or teleostean fishes of the present day.

The characters of the exo-skeleton, upon which Agassiz mainly relied, are so convenient for the geologist that they may still be usefully employed, although subordinate to a more natural classification. Two of

FIG. 20.—*Placoid.* *Cycloid.* *Ctenoid.* *Ganoid.*

the more essential of these characters are the form of the scales and that of the tail. The former he designated according to their shape and appearance.

The placoid is not a true scale, but only the ossified dermal papillæ, and osseous scutes of sharks, rays, etc. Agassiz also observed that in all

[1] For range in time of the Mollusca, see Woodward's 'Manual' and Davidson's 'Monographs on the Brachiopoda,' Palæon. Soc. 1850–1883.

living fishes, with the exception of some of the Elasmobranchii, the tails are equally divided into two lobes (homocercal), Fig. 21, B; whereas in the greater number of the extinct genera, the vertebral column, instead of stopping at the base of the lobes, is prolonged into the upper lobe, which is longer and larger than the lower lobe; these he termed 'heterocercal,' Fig. 21, A. This is a character which conveniently serves to distinguish the Palæozoic fishes, all of which have heterocercal tails; whereas fishes with homocercal tails do not appear before the Triassic period.

FIG. 21.—A, *Heterocercal Tail of Sturgeon*: B, *Homocercal Tail of Herring.*

In drawing out the following Table, I have therefore adopted that arrangement which seems to me most convenient for geological reference. As a rule, the classification of Owen and of Huxley is followed, but, with the teleostean fishes, Agassiz's grouping generally is adopted, with some modifications, suggested by Dr. Günther's recent work[1]. In this new classification the Sharks, Rays, and Ganoid fishes are comprised in one sub-class, based upon a concurrence of important external characters and internal organisation. This sub-class, which he has termed *Palæichthyes*, stands to the Teleostei in the same relation as the marsupials to the placentals,—being geologically, as a sub-class, the predecessors of the Teleostean Fishes. Dr. Günther further observes, as a remarkable fact, that all those modifications which show an approach to the ichthyic type of the Batrachians are found in this sub-class.

			EXAMPLES OF GENERA FOUND FOSSIL.
1. Elasmobranchii (Chondropterygii). *Skeleton cartilaginous, or partially ossified. No true scales, but ossified papillæ and dermal spines. Tail generally heterocercal.*	Plagiostomi. *Teeth numerous, some sharp pointed and compressed, others flat and crushing.*	Squalidæ or Selachii.	*Gyracanthus, Onchus.* *Cochliodus.* *Acrodus, Psammodus.* *Ptychodus.* *Hybodus, Orodus.* Lamna. *Notidanus.* Carcharodon.
		Raiidæ	Pristis. *Myliobates.* *Cetobates.* *Cyclobates.*
	Holocephali. *Jaws bony and encased with dental plates.*	Chimæridæ	*Ischiodus.* *Ganodus.*
		Edapodontidæ... ...	*Edaphodon.* *Elasmodus.*

[1] 'An Introduction to the Study of Fishes.' A. & C. Black, 1880.

			EXAMPLES OF GENERA FOUND FOSSIL.
2. Ganoidei. *Skeleton cartilaginous, or ossified. Exoskeleton in most cases formed by enamelled scales.*	Placodermi. *Head and fore-body encased in bony sculptured plates.*	The Ostracostei of Owen.	*Coccosteus.* *Pterichthys.* *Asterolepis.*
	Cephalaspidæ. *Head and body covered with bony plates.*		*Cephalaspis.* *Pteraspis.*
	Dipnoi. *Scales cycloid; tail diphycercal or heterocercal.*	Sirenidæ	Ceratodus.
		Ctenododipteridæ ...	*Dipterus.* *Heliodus.*
		Phaneropleuridæ ...	*Phaneropleuron.*
	Chondrosteidæ. *Dermal plates; heterocercal tail.*	The Sturionidæ of Owen.	*Chondrosteus.* Acipenser.
	Pycnodontidæ. *Obtuse teeth on the palate and the sides of the mandible; tail homocercal.*	*Pycnodontes*, Owen. *Pycnodontoidei*, Günther.	*Platysomus.* *Pycnodus.* *Gyrodus.* *Microdon.* *Mesodon.*
	Lepidosteidæ. *Rhomboidal enamelled scales; heterocercal or homocercal tail.*	The Lepidosteidæ, Sauridæ, Spenodontidæ of Günther.	Lepidosteus. *Lepidotus.* *Æchmodus.* *Dapedius.* *Palæoniscus.* *Ophiopsis.*
	Crossopterygidæ. *Scales thick and rhomboid, or thin and cycloid; heterocercal tail.*	The sub-order of *Polypteroidea*, Günther. Lepidoganoidea (part), Owen.	*Holoptychius.* *Osteolepis.* *Megalichthys.* *Diplopterus.* *Glyptolepis.* *Rhizodus.*
	Acanthodidæ. *Scales small and similar to shagreen; heterocercal tail.*	Lepidoganoidei (part), Owen.	*Acanthodes.* *Cheiracanthus.* *Diplacanthus.*
	Amioidei, Günther. *Cycloid scales; tail homocercal; vertebræ more or less ossified.*	Sub-order as enlarged by Günther.	*Caturus.* *Leptolepis.*
3. Teleostei. *Skeleton ossified, with completely formed vertebræ, usually deeply biconcave. Tail apparently symmetrical or homocercal.*	Ctenoidea. *Scales rough, with their free margins denticulated* (Ctenoid).	Percidæ	Labrax. Smerdis. *Cyclopoma.* Dules.
		Sparidæ	Sargus. *Sparnodus.*
		Berycidæ	Beryx.
	Cycloidei. *Scales smooth, flexible, circular, or elliptical* (Cycloid).	Labidæ	Labrus. *Phyllodus.*
		Mugildæ	Mugil.
		Scombridæ.	Scomber. *Isurus.*

			EXAMPLES OF GENERA FOUND FOSSIL.
3. Teleostei—*continued.*	Cycloidei. *Scales smooth, flexible, circular, or elliptical* (Cycloid).	Salmonidæ	*Osmeroides.* *Aulolepis.* Osmerus.
		Clupeidæ...	Clupea. Eugraulis. Spaniodon. *Rhinellus.* *Scombroclupea.*
		Cyprinidæ	Barbus. Gobio. Acanthopsis. *Cyclurus.*
	Acanthini. *Body generally naked, or with very small scales.*	Gadidæ	Gadus. *Rhinocephalus.*
		Pleuronectidæ... ...	Rhombus.
4. MARSIPOBRANCHII	No fossil forms known. (? *Conodonts*).		
5. PHARYNGOBRANCHII			

The remains of Fishes are not met with until the upper division of the Silurian rocks is reached. They soon become numerous, and abound in the next overlying Devonian series.

The **Ganoids** are the predominating fishes of the Palæozoic series. A large number die out after that period; and the genera continue to diminish up to the present time.

The **Elasmobranchii** (Placoids of Agassiz), which include the Sharks, Rays, etc., are as ancient as the Ganoids; but they are more largely developed in the Secondary rocks, and become still more numerous in the Tertiary times. The teeth of the Shark tribe are covered with a hard enamel, which has favoured their preservation. The crushing teeth of the Rays, which are arranged like a mosaic pavement on the jaws and palates, are also among the common fossils of the Secondary and Tertiary strata.

Of the **Teleostean Fishes** none are known of earlier date than the Cretaceous series; they increase in numbers in the Tertiary period, and attain their maximum in the present seas.

II. **AMPHIBIANS.** This class of animals is allied to the ordinary Reptiles; but, whereas in the latter the skull articulates with the vertebral column by means of one occipital condyle, in Amphibians it articulates with two. It is only by the cast and impressions of footprints that the presence of Amphibians in some geological periods has been inferred. The smaller size of the front foot, the possession of five toes, the outward position of the short thumb-toes and at nearly right angles to the line of the mid-toe, the absence of claws, the toes being terminated by pellets, and

the soft rounded form of the whole, are the characteristic features of these impressions. They vary very greatly in size. Amphibians are divided into four orders:—

1. OPHIOMORPHA. No fossil forms.
2. Urodela (tailed Amphibians—Salamandroids).
3. Anoura (tail-less Amphibians—Batrachians).
4. *Labyrinthodontia.*

The Amphibia make their appearance somewhat later than the fishes: the **Labyrinthodonts** commence in the Carboniferous, and are the dominant order during the Permian and Triassic periods, at the end of which they become extinct. A salamandroid reptile (*Protriton,* Gaud.) occurs in the Permian. The tail-less Amphibians, on the other hand, such as the frogs, do not appear until the Tertiary period.

III. **REPTILES.** The skeleton of this class of animals is distinguished by the circumstance that the skull is attached to the vertebral column by one occipital condyle articulating with the atlas; that the lower jaw is complex, each ramus being composed of from four to six pieces united by sutures; that the lower jaw articulates with the skull by a separate bone (the quadrate bone) instead of directly as in Mammals; and that the teeth have but one fang, and are not generally sunk in separate sockets or alveoli. The centre of the vertebræ may be concave on both sides, or concave only in front, or only on the back, or they may have nearly flat articular faces.

Reptiles are divided into the following living and extinct classes:—

1. Chelonia ...	... Turtles and Tortoises.
2. Ophidia ...	... Serpents. (*Palæophis,* etc.)
3. *Enaliosauria*	... *Marine Saurians.* (*Ichthyosaurus, Plesiosaurus,* etc.)
4. Lacertilia ...	... Lizards. (*Mososaurus, Telerpeton,* etc.)
5. *Thecodonta*	... Sheath-toothed Reptiles. (*Thecodontosaurus, Belodon,* etc.)
6. Crocodilia ...	... Crocodiles. (*Teleosaurus, Dakosaurus,* etc.)
7. *Dicynodonta*	... *Canine-toothed Reptiles* (only found in Africa and India.)
8. *Dinosauria*	... *Land Saurians.* (*Iguanodon, Megalosaurus.*)
9. *Pterosauria*	... *Flying Reptiles.* (*Pterodactyles,* etc.)

Reptiles make their first appearance in the Permian period, and attain their maximum development in the Secondary or Mesozoic period, which is, in consequence, sometimes called the 'Age of Reptiles[1].'

The gigantic **Enaliosaurians,** or the marine saurians, including the extraordinary extinct Ichthyosaurus and Plesiosaurus,—reptiles which were probably covered with a smooth or wrinkled skin, and were furnished with strong and powerful paddles for swimming,—abound in the Lias and in some other parts of the Jurassic series, and extend to the Chalk.

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[1] See Owen's '*Reptilia* of the several Geological Formations,' in Palæont. Soc. 1848-1883.

The wonderful **Dinosaurians,** or the land saurians, range from the Triassic to the Cretaceous series inclusive.

The **Pterosaurians,** or flying reptiles, belong also exclusively to the Secondary period, and range from the Lower Lias to the Middle Chalk.

The **Crocodilia** (which are distinguished from the Lizards by their covering of scales or scutes, and the lodgment of the teeth in distinct sockets) commence also in the Trias (Stagonolepis), but true Crocodiles, such as those of living species, do not appear before Tertiary times.

Chelonians commence with the Stonesfield (Great Oolite) beds. They increase in the Upper Jurassic and Cretaceous series; and in the Tertiary strata the remains of Turtles, together with several fresh-water genera, are often very abundant. True land Tortoises do not appear before the Miocene or Middle Tertiary period. **Serpents** appear early in the Tertiary period.

IV. **BIRDS.** The bones of Birds are characterised by their comparative lightness and by their more cavernous structure. In living Birds the margins of the bill are sometimes serrated, but teeth are never developed; true teeth are however present in several fossil species. The footprints of Birds are tridactyle, which serves generally, but not always, to distinguish them from those of Reptiles. Birds are divided into—

1. Natatores	Swimmers	Ducks, Gulls, etc.
2. Grallatores	Waders	Herons, Snipes, etc.
3. Cursores	Runners	Ostrich, *Dinornis*, etc.
4. Rasores	Scratchers	Fowls, Pheasants, etc.
5. Scansores	Climbers	Parrots, Woodpeckers, etc.
6. Insessores	Perchers	Crows, Starlings, Finches, etc.
7. Raptores	Birds of prey	Eagles, Vultures, etc.
8. *Saururæ*	(Lizard-tailed) ...	*Archæopteryx.*

We have no reason to suppose that Birds were less common in some of the geological periods than they now are; but, from their mode of life—their not being subject to the effects of floods, etc., very few of their remains have been fossilised. Their existence is inferred in early Secondary or Triassic times from footprints alone. The first unmistakeable remains are those of the Solenhofen beds, which are of Upper Oolitic age. They are there represented by the singular Archæopteryx, a genus in which the vertebral column is lengthened into a tail of many joints; while there is reason to believe that teeth were implanted in the jaw. In the Cretaceous strata remains of wading birds have been found. In the Tertiary strata Birds become more common, including new classes and species of vulture, kingfisher, parrot, petrel, crane, together with gigantic wingless birds.

Swimmers first appear in Tertiary times. Portions of the shells of eggs, supposed to be those of ducks or geese, are said to have been found in Post-glacial river-deposits.

V. **MAMMALS.** In this class the following points may serve as guides to the student. The skull is connected with the vertebral column by

means of two condyles articulating with the atlas—a feature common with the Amphibians, but distinguishing them from the Reptiles; the lower jaw articulates directly with the skull without the intervention of a quadrate bone; the centra of the vertebræ are usually flat at each end; the teeth are implanted in distinct sockets, and consist, when most completely developed, of three groups—incisors, canines, and molars, which latter have two or more fangs. The mammalia are divided into fourteen orders.

			FOSSIL GENERA.
Aplacental	1. MONOTREMATA ...	Duck-mole, etc.	
	2. Marsupialia	Kangaroos, Opossums, etc. ...	*Amphitherium.*
Placental	1. Sirenia	Manatees, Dugongs	*Halotherium.*
	2. Cetacea	Whales, Dolphins, etc.... ...	*Balænodon.*
	3. Pinnipedia	Seals, Walruses	*Pristiphoca.*
	4. Ruminantia	Deer, Oxen, Camels, etc. ...	*Megaceros.*
	5. Solipedia	Horses, Zebras	*Hipparion.*
	6. Pachydermata ...	Tapirs, Pigs, etc.	*Anoplotherium.*
	7. Proboscidea	Elephants, etc.	*Mastodon.*
	8. Rodentia	Hares, Beavers, etc.	*Trogontherium.*
	9. Edentata	Sloths, Armadillos, etc ...	*Megatherium.*
	10. Carnivora	Tigers, Hyænas, Bears, etc....	*Machairodus.*
	11. Insectivora	Moles, Hedgehogs, etc. ...	*Palæospalax.*
	12. Cheiroptera ...	Bats, Vampires, etc.	*Rhinolophus.*
	13. Quadrumana... ...	Monkeys, Apes, etc.	*Pliopithecus.*
	14. Bimana	Man.	

Species of all these orders, with one exception, have been discovered in a fossil state. No extinct order is known, unless we except certain extraordinary Eocene forms of North America which are considered by Prof. Marsh to have very distinct characters and for which he has founded two new orders—the Dinocerata and Tillodontia—intermediate between the Ungulata and Proboscidea. As, with the exception of the Cetacea, Sirenia, and Pinnipedia, all the Mammalia are land animals, their remains have not had the same chances of entombment in ordinary marine strata as those of the marine animals living in the seas where the deposition of sedimentary strata was always going on: and as lacustrine and fluviatile are of very limited occurrence in proportion to the extent of marine strata, the remains of land animals are scarce and occur only at long intervals. Consequently, the geological record is in this direction more imperfect than in others[1]. The earliest known Mammal, nearly related to the little marsupial Myrmecobius, or ant-eater of Australia, occurs in the Rhœtic or Upper Trias of Stuttgart and Somerset. A few small Marsupials have also been found in the Stonesfield slate (Great Oolite), and others again in the Purbeck strata. The remains of no placental mammalia have yet been discovered in any strata of Secondary age. With the insetting of

[1] For the distribution of the Mesozoic Mammalia, see Owen, Palæon. Soc. 1871; for those of the Tertiary period, M. Gaudry's 'Enchainements du Monde Animal,' and for the Quaternary period, Prof. Boyd Dawkins, 'Quart. Journ. Geol. Soc.' for Nov. 1872.

the Tertiary strata, such remains become common; and the Mammalia have constantly increased to the present day, when they culminate in importance and development.

Although so many of the links of the chain are wanting, there is reason to believe that the remaining members in this, as in other classes, fairly represent the relative character of the life prevailing in the several geological periods; for in each series, although entirely marine sediments and marine organisms largely prevail, there are a certain number of strata in which the land element is sufficiently marked to ensure a recurrence from time to time of those conditions which would lead 'mutatis mutandis' to the preservation of the analogous class of terrestrial remains at the periods when these recurring conditions obtain.

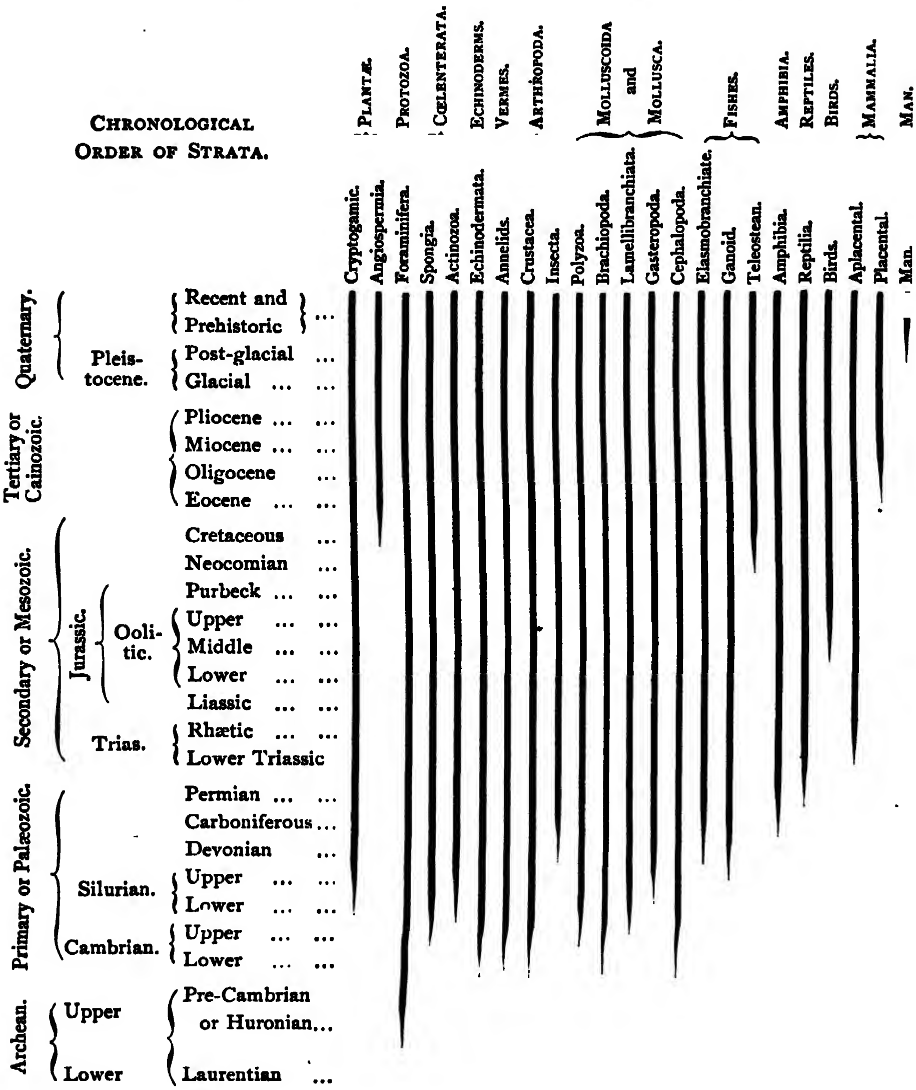
The range in time of these several classes of the vegetable and animal kingdoms is given in the Table on the opposite page. Although, with the exception of the Angiospermous plants and the Placental mammalia, they all extend far back in the geological series, they differ widely in relative importance at each geological age, as is broadly shown by taking the present distribution of species of the several classes of the animal kingdom and of plants in the British area, and comparing it with that which obtained at two distinct geological periods.

		Silurian Period.	Jurassic Period.	Recent Period.
	Mammals	—	5	76
	Birds	—	1[1]	354
	Reptiles	—	89	15
	Fishes	12	191	263
Molluscs.	Cephalopods	97	435	13
Molluscs.	Univalves	102	823	325
Molluscs.	Bivalves	132	1035	220
Molluscs.	Pteropods	40	—	2
Molluscs.	Brachiopods	263	185	7
Molluscs.	Polyzoa	140	60	161
	Crustacea	307	45	278
	Annelids	36	37	21
	Echinoderms	90	194	50
	Zoophytes...	87	163	137
	Protozoa	21	42	96
	Plants	4	160	1820

It must however be remembered that the Silurian and Jurassic periods both represent very long periods and successive groups of life, whereas the present period is of short duration and represents but one group.

[1] This is not British, but relates to the Archæopteryx of Solenhofen.

PERIODS OF THE FIRST APPEARANCE AND RANGE OF THE SEVERAL CLASSES OF THE VEGETABLE AND ANIMAL KINGDOMS IN THE EUROPEAN AREA.



CHAPTER VI.

SEDIMENTARY STRATA—HOW FORMED; RIVER AND SEA EROSION.

Bearing of Present Causes. Rain. Transporting Power of Water. Formation of Deltas and Coast-Deposits. Deltas of the Rhone, the Po, the Nile, the Rhine, the Ganges, the Mississippi, the Danube. Age of Deltas. Formation of Valleys. River-Terraces. Old River-Channels. The Cañons of Colorado. Coast waste. Origin of Channel Coast-Shingle. Cliffs. Wear of Coast. Contemporaneous Organic Remains. Mixing of Terrestrial and Marine Remains. Such Remains typical of the Life of the Period. Analogy of Recent Sediments with their embedded Organisms to the Strata and Organic Remains of Geological Periods.

Existing Causes. The geologist has to study the effects of the agencies at present acting on the surface of the globe, in so far as they are of a nature to furnish evidence which may assist in the interpretation of the mode of formation of the sedimentary strata, of the disturbances to which these strata have been subjected, and of the succession of life of which they contain the remains.

Although the causes relating to these phenomena are to be judged of by our knowledge of the causes which produce analogous results at the present time, we have to see that in each case the range of our experience is a fair measure of all the phases of the phenomena into which we have to inquire. Our first subject of inquiry relates to the manner in which the sedimentary strata have been built up; and for this purpose we have to consider the effects of the various meteoric agents, such as rain, wind, surface-waters, heat, snow, and ice, which are constantly modifying the surface of the globe. By their action the land is unceasingly disintegrated, and the disintegrated portions transferred from the land to the sea, thus denuding and lowering the one, and adding to and raising the bed of the other. The falling rain, in running off the surface, carries with it particles of the soil, and the resultant streamlet transports them, with additions from its own channel, to the river. This, the most important of these agents, we will take first.

Rain. In passing down any large river such as the Thames after heavy rains and floods, no one can have failed to observe the discoloration of the water caused by the greater and lesser quantity of mud or silt at such times held in suspension. The quantity varies in different rivers according as they flow over hard (granite, limestone, etc.) or soft rocks (sands,

clays, etc.). This silt is ultimately carried out to sea, where, as the velocity of the water is checked, it is gradually deposited in the form of shingle, sand, or mud, in banks such as those which accumulate at the mouth of the Thames, Severn, Seine, or other large rivers.

The nature of the sediment will depend on the geological character of the country through which the river flows, and on the velocity of the stream. While some streams will have force to transport shingle, others will transport only sand, and others fine silt. In the same way, when carried out to sea, the sediment is transferred to greater or lesser distances according to the force of the tides and currents sweeping the coast. Although the distance over which the sediment may be spread is variable, the order in which it is deposited is definite. The coarser and heavier shingle will be stayed first, the sand next, and the finer silt or mud will be transported to the greatest distance. The mud of the Severn discolours the waters of the Bristol Channel, and leads to the formation of shoals for many miles distant from the mouth of the river; the German Ocean becomes slowly but gradually shallower in consequence of the silt and débris carried down by the Thames, Rhine, and other rivers.

The transporting power of water varies according to the velocity of the current. This is greatest in the centre of a river, and least at the borders. The velocity of the particles in contact with the bed is about as much less than the mean velocity as the greatest is greater than the mean. In ordinary cases the least, mean, and greatest velocities may be taken as bearing to each other nearly the proportion of three, four, and five. The following are the effects in the removal and transport of various materials by currents of given velocities acting on the bed of a river[1]:—

Soft clay requires a velocity of	0·25 foot per second.
Fine sand ,, ...	0·50 ,, ,,
Gravel as large as French-beans requires a velocity of . .	1·00 ,, ,,
Gravel of pebbles one inch in diameter requires a velocity of	2.25 feet per second.
Larger blocks of rock require a velocity of . . .	6·00 ,, and upwards ,,

The late Mr. W. Hopkins, of Cambridge, has stated that the 'force exerted on a surface given in magnitude and position is found to increase with the square of the velocity.' And if the force of the current be estimated by the weight of the largest block, of a given form, which it is capable of transporting, it is found that the force varies as the *sixth power of the velocity of the current.* Thus a certain current being able to move a cube of given weight, another current of double the velocity would move a cube of 64 times the weight of the former; if the velocity were treble that of the first case, the cube moved might be 729 times as great, and so on[2].

[1] Rankine's 'Civil Engineering,' 10th Edit., pp. 674 and 748.

[2] 'Quart. Journ. Geol. Soc.,' vol. iv. pp. 92 and 93.

In this manner a spherical block of 5 tons might be moved by a current of 10 miles an hour; a current of 15 miles per hour would move a block of 56 tons; and a current of 20 miles, blocks of 320 tons and upwards. This is a consequence of great importance to geologists; for, while a current of 2 to 3 miles an hour would hardly move a pebble, blocks of great size are moved by a comparatively small increase of velocity.

As the velocities of currents in the sea diminish with distance, or by clashing with other currents, and are strongest near the land and in shallow waters, the larger blocks and shingle rarely travel far from shore; grit and coarse sand travel farther out; while the finer sediments are carried to considerable distances from land. The ocean off the coast of South America has been found discoloured at a distance of 300 miles from land by the turbid waters of the River Amazon, but this is an exceptional case.

Deltas. When the rivers empty into tidal seas with conflicting currents, the sediment they carry down is swept away and deposited as shoals and banks over the bed of the adjacent seas, as in the case of the Thames, the Severn, and the Seine, and delta-formation does not take place. But when the tides are small and the currents of less force, the sediment falls quickly, or is carried only to short distances on either side of the embouchure of the river, where it is deposited on the fronting shoals, which are eventually raised above the sea-level, and form low lands and flats which gradually advance and gain on the sea, so that, instead of a retreating estuary, we finally have an advancing low promontory. These are the conditions which determine the formation of deltas, some of the most important of which, as illustrating the formation of sedimentary strata, we will now proceed to describe. The deeper sea deposits will be noticed in another chapter.

FIG. 22.—*Delta of the Rhone.*

The Rhone[1]. It is calculated that the body of water discharged annually by this river carries down with it 24,000,000 cubic metres of silt,—a mass sufficient to cover 1000 hectares (2500 acres) to the depth of about 7 feet. This has led to

Elie de Beaumont in his 'Leçons de Géologie pratique,' pp. 253–521, gives detailed accounts of this and other of the most important deltas of the world. He likewise describes very fully a number of littoral deposits. See also Lyell's 'Principles of Geology,' 10th Edit., chaps. xviii. and xix.

a rapid growth of the delta of this river. In the time of the Romans, 400 B.C., Arles was at a distance of 14 miles from the sea, now it is 30 miles distant, the delta having within the last 2200 years advanced 16 miles. Its progress is still rapid, for a lighthouse built near the mouth of the river in 1869 was in 1874 distant 131 feet from the sea. The depth of the deposit is also considerable. A well sunk in the delta at Aigues Mortes passed through a thickness of 328 feet of marls and clays, belonging to this modern deposit, without reaching the substrata on which it rests[1].

A striking feature of this delta is that, while on its extensive flat and marshy lands (La Camargue) not a single pebble is found, it is flanked—but more especially on the east—by great banks of rolled pebbles of variolite, serpentine, protogine, quartzites, schists, etc., from rocks not belonging to the Upper-Rhone valleys, but coming from the French Alps to the eastward. The well sunk in the delta traversed fine river silt, but towards the bottom a few pebble beds were met with.

The Po carries down in floods as much as $\frac{1}{300}$ part (by weight) of solid matter (Lambardini); and has formed deposits which have extended

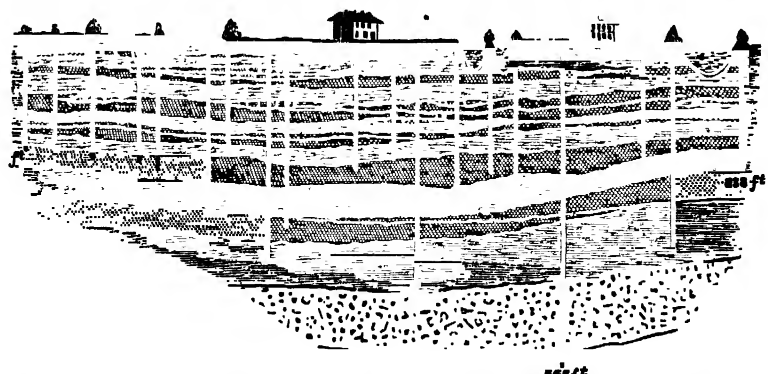


FIG. 23.—*Section of the delta deposits of Venice, with overflowing artesian wells* (after C. Laurent[2]).

21 miles out to sea. Their progress during the last hundred years has been at the rate of about 300 feet annually. It is on the delta formed by the Po, in conjunction with other minor rivers, that Venice, Ravenna, and other towns and villages now stand. Artesian wells sunk at the former city prove the modern accumulations to be not less than 566 feet in thickness.

The sections of these wells afforded an unrivalled opportunity for studying the structure of a delta and the range of its beds. In this case the deposit was found to consist of a variable series of beds of sand, clay, hard concreted seams, and shingle,—a variability due to the irregularity of seasons, action of floods, and set of the currents; fig. 23.

The Nile, in times of flood, is loaded with sediment. Owing, how-

[1] C. Martins, 'Revue des Deux Mondes,' Feb. 1874.

[2] 'Bulletin Soc. Géol. de France,' 2nd Ser., vol. vii. p. 481.

ever, to the annual overflow of this river the greater part of the sediment is deposited on the neighbouring land, which is raised by it about 6 inches in a century. The base of the pedestal on which stands the statue of Rameses the Second, erected 3212 years ago, is now 9½ feet below the surface of the ground[1]. Borings made there show that this old Nile mud extends to a further depth of 39 feet without reaching the bottom. In consequence of the deposit going on the land, comparatively little sediment is carried out to sea, and that little, being met by strong currents, is swept away to the deeper parts of the Mediterranean, so that the delta now gains little or nothing on the sea, and the coast is changed but very slightly from what it was 3000 years ago. The head of the delta extends inland to a distance of 85 miles from the coast.

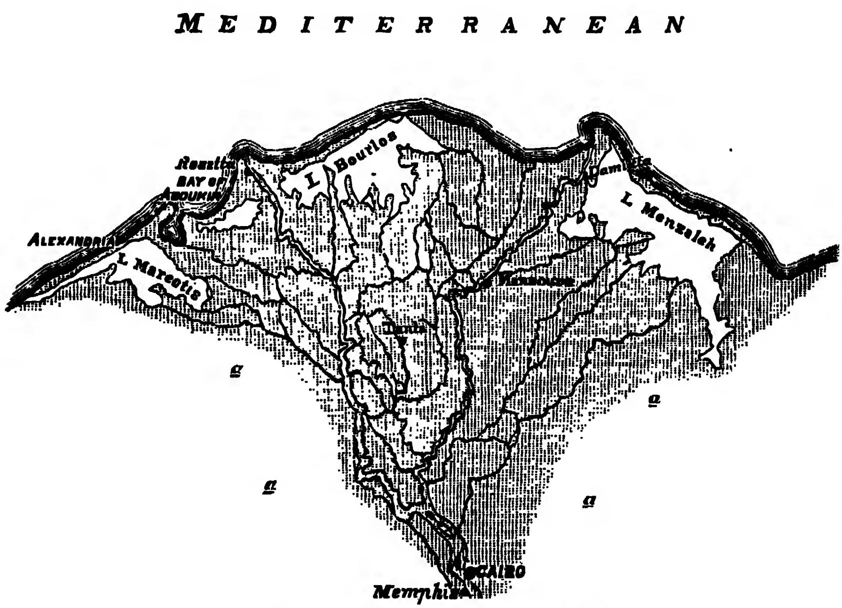


FIG. 24.—*Delta of the Nile.* *a.* Strata of Tertiary age.

The Rhine. According to Mr. Horner[2], the quantity of sediment carried down by this river amounts to one in 1600 parts of water. The volume of water being very large, the delta is of great extent, embracing the greater part of Holland, and stretching 80 to 90 miles inland from the present coast. A well at Amsterdam traversed 224 feet of the delta-deposits, and another at Utrecht was sunk 410 feet without passing

[1] L. Horner, 'Phil. Trans.' for 1855, pp. 53–92. A recent boring has been made, by the aid of a grant from the Royal Society, at Tantah in the middle of the delta. After passing through 58 feet of sands a bed of clay 15 feet thick was traversed, and below that a water-bearing sand was found, the water from which rises to the surface. The substratum of rock was not reached.

[2] 'Edin. New Phil. Journ.,' vol. xviii. p. 102.

through them [1]. The section of the former will serve to show the general character of this delta.

SECTION OF A WELL AT AMSTERDAM.

	Feet.
Peaty sand	51
Layers of sand and clay	22
Blown (?) sand	14
Beds of sand with marine shells	55
Hard clay without shells	49
Sand and *pebbles*	13
Pure sand	20
	224

The Ganges. The mean annual discharge of water by this river amounts to 200,579 cubic feet per second, and during floods it contains as much as $\frac{1}{428}$th part (by weight) of silt, equal to 577 cubic feet carried down per second [2]. The quantity carried down in the course of a year has been estimated to be sufficient to cover a surface of 2736 square miles to the depth of 1 inch, so that an area larger than most English counties would be covered with sediment to a depth of more than 8 feet in the course of a century. The head of this great delta, which has an area of nearly 8000 square miles, extends to a distance of 220 miles from the sea. In 1840, an artesian well at Calcutta was carried to a depth of 481 feet, all through this delta deposit, without reaching the bottom of it. The following section is given by Mr. Medlicott [3]. The italics are mine.

SECTION OF THE WELL AT FORT WILLIAM, CALCUTTA.

	Feet.
Surface soil, loose sand, and clay	10
Adhesive blue clay	15
Ditto. with peat	10
Adhesive clay	5
Dark clay with decayed wood intermixed	10
Calcareous clay with kankar (calcareous concretions)	10
Green sandy clay / Sandy clay with kankar / Variegated arenaceous clay	60
Argillaceous marl	5
Loose sandstone	5
Argillaceous marl	20
Arenaceous clay with *weathered mica-slate* and nodules of hydrated oxide of iron	20
Calcareous clay	5
Coarse friable *quartzose conglomerate*	10
Micaceous clay	20
Soft sandstone	5
Ferruginous sand intermixed with clay	90
Fine loose sand with minute *fragments of felspar and granite*	25
Sandstone slightly aggregrated (first fossiliferous stratum—*bone of ruminant*)	55
Shelly calcareous clay (fragments of freshwater shells)	5
Carbonaceous bed	10
Coarse conglomerate (third fossiliferous stratum 430 feet)	86
	481

[1] 'Comptes Rendus,' 10 August, 1835.

[2] Rev. Robert Everest, 'Asiatic Soc. Journ. for 1832,' pp. 238 and 549.

[3] 'Records Geol. Survey of India,' vol. xiv. p. 221, and 'The Geology of India,' p. 399.

Mr. Medlicott calls attention to the occurrence at a depth of 175 to 185 feet, again at 300 to 325 feet, and again throughout the lower 85 feet of the borehole, of pebbles in considerable quantity and size. He adds that 'the greater part of the pebbles were clearly derived from gneissic rocks, but some fragments of coal and lignite which were obtained were perhaps from the Damuda series.' These rocks do not come to surface within less than 200 to 300 miles from Calcutta.

The Danube. I will now take an instance of a large river discharging into an inland sea. From observations carried on for a period of ten years at the Sulina mouth of the Danube, Sir C. A. Hartley determined that the mean weight of detrital silt to the weight of water was as 1 : 3060, and calculated that the total detritus discharged per annum amounted to 67,760,000 tons, or equal to a mound 20 feet high covering 14 square miles of surface [1].

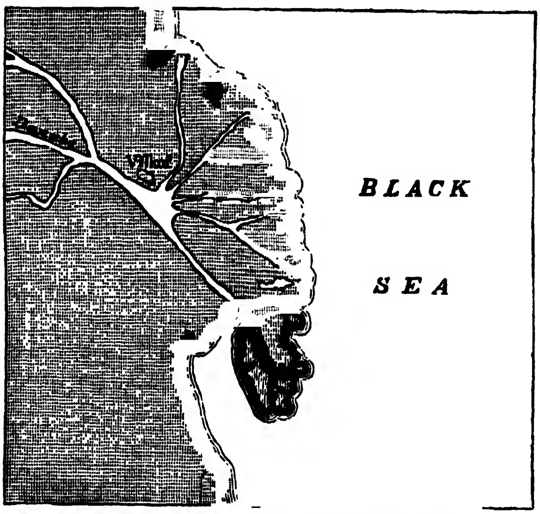


FIG. 25.—*Delta of the Sulina branch of the Danube.*

It would be interesting if sufficient data could be obtained to try to form some estimate (though it would be an extreme one) of the time that it would take for such a delta to accumulate and for a sea like the Black Sea to be silted up. Knowing its area and its average depth, the time required at the present rate of deposit might be approximately determined. And, if the area of the delta could be ascertained together with its depth, a clue might also be furnished as to the age of the delta itself, and consequently to the antiquity of the basin of the Black Sea.

The Mississippi[2]. The quantity of sediment carried down by this river is even larger than that by the Ganges, and its delta is advancing into the Gulf of Mexico at the rate of 338 feet annually. The whole area covered by the delta is about 12,300 square miles, while the deposits of which it is formed have been found, by a boring made at New Orleans, to be more than 630 feet thick.

Age of Deltas. Some attempts have been made to estimate the

[1] 'Min. Proc. Inst. Civ. Engineers,' vol. xxxvi. p. 214.

[2] See Humphrey's and Abbot's Report 'On the Physics and Hydraulics of the Mississippi River,' 1861; and Lyell's interesting account of the same, *Op. cit.*, vol. i. pp. 440–466.

time taken for the formation of deltas. According to Mr. Horner, it would have required, at the present rate of deposit, 13,500 years to accumulate the 39 feet of Nile sediment which underlies the statue of Rameses. This would give for this portion of the delta a period of about 17,000 years. It has also been calculated that not less than 21,600 years would be needed for the delta of the Ganges, while for that of the Rhone one geologist formed the low estimate of 6500 years. But it is difficult to form correct estimates of the age of deltas with the data in our possession; they cannot certainly be calculated altogether at the present rate of deposition, and as most deltas go back in all probability to the glacial period, they must originally, with the greater floods of those times, have grown more rapidly formerly than at present. Again, as the rocks inland become barer, and the gradients less, the quantity of material carried to sea must become annually smaller.

In the case of the Ganges, Mr. J. Fergusson[1] also objects to the above-named measure of time on the grounds that the Ganges deposit is a very variable one, a depth of 40 feet having in his experience been accumulated in a year at one place, while in others it did not exceed 1 foot; and he shows that the changes in historical times have been such as to render it probable that until the fourteenth century the greater part of Bengal proper was a vast lagoon; and that within 5000 years the sea probably extended to, or near to, Raj Mahal near the head of the delta. But this very variability equally affects estimates based too exclusively on a maximum rate of deposit. I have seen the impounded flood-waters of the Severn form a deposit 1½ feet thick in a year; but it does not follow that this gives a measure of the growth of the Severn delta. It is the mean deposit over the whole area that must be taken into account, and this no doubt is better determined by the discharge of water and the proportion of contained sediment, than by exceptional deposition under favouring circumstances of shelter, etc. At the same time, there is no doubt that exceptional seasons should be taken into account, and especially the exceptional conditions which may have prevailed during the early stages of delta growth, in consequence of the climatal conditions different from the present which certainly then prevailed over the northern hemisphere.

In fact it is evident from the well sections given above that many rivers, which now only carry down silt and mud to the sea, formerly had power enough to transport much coarser materials, and even pebbles of considerable size. In the delta of the Rhone pebbles were found at a depth of about 300 feet. At Amsterdam a bed of 13 feet thick of sand and pebbles occurred at a depth of 191 feet; while the section of the

[1] 'Quart. Journ. Geol. Soc.,' vol. xix. p. 321.

Ganges delta, with its basement bed of large pebbles, shows even a stronger transporting power, and indicates a more rapid rate of deposition.

River-Denudation. The dimensions of the deltas necessarily give the measure of the wear of the land-surfaces to which they owe their origin —the growth of the one going on *pari passu* with the erosion of the other; for, while sedimentary deposits are thus gradually accumulated in the bed of the sea or estuary, and its depth is gradually rendered shallower, the hills and mountains of the land are being slowly worn away and lowered by the action of the rainfall, which passing charged with their débris into the rivers, and thence out to sea, carries with it the materials necessary for the formation of deltas and submarine beds.

There is, moreover, carried down to the sea by rivers not only sediment mechanically suspended, but also mineral matter in solution. The matter in solution consists, as will be shown in the next chapter, in large part of carbonate of lime. River-sediment, on the contrary, contains little or no lime, but consists chiefly of silica, alumina, and iron-peroxides in variable proportions, with some magnesia and organic matter. As a type of these, we may take the silt of the following rivers:—

	Rhine. (*Müller*)	Nile. (*Horner.*)	Loire. (*Delesse.*)
Silica	55·43	54·58	74·59
Alumina	17·05	11·65	
Carbonate of lime	4·60	3·72	4·75
" magnesia ...	2·17	0·0	
Sulphate of lime	0·0	0·24	0·0
Potash and soda	0·0	1·03	0·22
Iron-peroxide	15·65	20·21	12·05
Lime, Magnesia	0·0	2·87	0·0
Organic and other matter	5·10	?	8·39
	100·00	100·00	100·00

Formation of Valleys. The action of rivers is two-fold. When the gradient is considerable, as it commonly is in the upper courses of the rivers, the action is to erode and excavate their channels; when, on the contrary, the rivers flow in their lower courses through a flat district with but little fall, their action is to deposit the sediment brought down from the higher reaches, and to raise the level of their own beds and of the adjacent flats by their floods. Such a river as the Po affords good instances of this. If, on the other hand, the country is of a hilly character, and a sufficient gradient is maintained to the coast-line, the river excavates a deep channel, bordered by heights, down to its mouth, as in the instance of the Tyne, the Tweed, and other rivers.

It is also possible, and has no doubt frequently happened up to recent times, that constant slow changes in the level of the land have, when

it has been a case of subsidence, tended to fill up and raise the land at the mouth of a river, as in the earlier alluvial stages of the Thames; while when there has been elevation of the land, and a persistent gradient has been maintained, the process of valley-excavation has been prolonged, extended to greater depths, and to near the sea-board. This has been the case with the Somme, the Avon (Hants), and other rivers, where in all probability a slow elevation of the land in Pleistocene times kept pace with the excavation of the valleys [1].

When the gradient of the river is steep throughout its course, it will excavate a more or less deep and narrow channel. With a lesser gradient and less definite course, it will stray from its channel and widen the valley under excavation. Where an area with even a small slope consists of inclined alternating beds of varying resistance, having a slight dip in the direction from which the stream flows, the erosion will go on rapidly in the softer lower beds, *b*, and be checked by the harder higher strata, *a*, so that these latter more resisting beds become undermined, and form a ledge over which the water falls. As a consequence of this operation, the rock, instead of being worn away, breaks down, and the débris being quickly removed by the eddies and currents, a uniform deep river-channel is worn by the retrocession of the water-fall, and no terraces are formed; but in place we may have a vertical incised cut or channel carried through a nearly level and maybe quite undisturbed district.

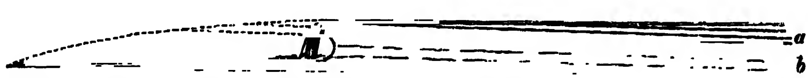


FIG. 26.—*Diagram Section to illustrate the formation of a narrow Valley or Gorge by waterfall action.*

But a different and more usual mode of valley excavation, especially when the ground consists of soft or homogeneous strata, and the gradient is moderate, as in such river basins as those of the Thames, the Seine, the Somme, and others, is for the river to deepen its channel simultaneously throughout, and at the same time to widen the valley. For, when, in periods of flood or from other causes, the river shifts its position, and attacks one side of the valley more than the other, the valley is enlarged unequally, the river undermining one side according to variation in the water power at particular times, and cutting back into the valley side. In this way the valleys often present gentle slopes and terraces on one side, and escarped banks on the other, against which the river has been at one time more strongly deflected, as with the Thames when its valley bed extended to the range of low Tertiary hills from Greenwich to Erith, or the several picturesque escarpments in the valley of the Evenlode,

[1] 'Phil. Trans.' for 1864, p. 297.

between Handborough and Charlbury, in Oxfordshire, or in the valley of the Cherwell, at Enslow.

As the old rivers gradually excavated the valley channels deeper, they left here and there portions of their drifted materials on terraces at the level at which they flowed at successive times. In the following section only two terraces are represented, but they may be more or less numerous. They are rarely or ever preserved entire, and have been often completely removed by subsequent denuding agencies.

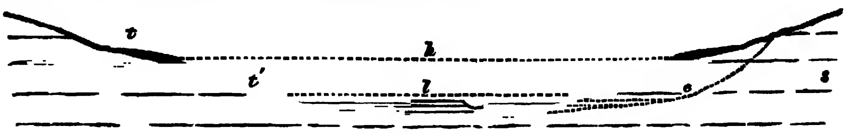


FIG. 27.—*Diagram Section of a Valley formed by ordinary river action.*

s. Horizontal and undisturbed strata, cut through by the river. *t*. Terraces of gravel left by the river when it flowed at those several levels, and before the excavation of the valley to greater depths. Thus, when the river flowed at the level *h* of the highest terrace, the Chalk or Oolites, or other strata below that level, still extended across the valley. This upper terrace *t* is therefore the oldest, and the lower one *t′* the newer, when the river flowed on to the level of *l*.

In nature this regularity of structure is never preserved. The terraces may have been destroyed for great lengths, and at various places, by the varying action of the river, or may be altogether removed by the cutting back of the sides at the later river-periods in the way represented by the dotted line *c*.

With respect to the river-drift of gravel, sand, and loam lodged on these high, *t*, and low-level, *t′*, terraces, they may or may not contain organic remains, but if they do, these remains consist of the débris of the land animals, and of the fluviatile and land shells, living at the period of the river's history when that particular terrace was formed.

An important point to notice in connection with these drifted materials is that they are all derived from strata higher up the same river-basin; thus in the valley of the Medway we find worn fragments of only Cretaceous and Wealden strata; in the valley of the Thames, fragments derived from the Drift, Tertiary, Cretaceous, Oolitic, etc. strata of the Thames Basin; while in the valley of the Severn, there occurs a more complex gravel, derived from rocks of Triassic and various Palæozoic ages, which are found in that hydrographical area. Thus therefore the evidence is clear, that not only have our valleys been formed by river action, but the old rivers were confined to the same basins as at present, and that if the water-power was greater (as we shall presently show to have been the case) it was due not to more extensive drainage areas, but to a greater rain-fall or greater floods dependent upon climatal conditions different to those which now prevail.

In those instances where the gradient has been moderate, and the river has worn for itself a valley of moderate width, as with the Thames, the Seine, the Somme, etc., it has left traces of its presence, at successively lower levels, in the form of river-shingle, and sometimes river-shells, left

high and dry above the river's present level in certain sheltered positions or in terraces. Or the lowering river, from changes in the level of the land or other causes, may, after excavating a portion of its valley, have been directed into a new channel, and the old one stranded waterless amongst the adjacent hills, as happens at least at one place with the Lesse in the Ardennes, and the Loire between Le Puy and St. Etienne, and in a smaller (very small) way with the Cherwell and the Thames between Kidlington and Yarnton above Oxford.

The process of valley-excavation is extremely well shown in the valleys of the Ardennes, where the rivers have cut their way to depths, in places of from 500 to 600 feet or more, through high plateaux of hard Palæozoic rocks levelled by old marine denudation. These valleys run through a series of strata, highly disturbed, but now planed down to a comparatively flat surface, and forming a table-land of high antiquity.

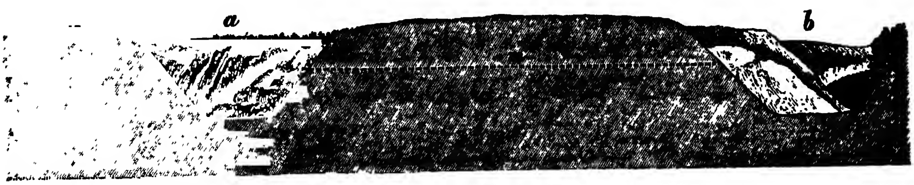


FIG. 28. - *Diagram section through a portion of the Ardennes* (in part after Dufresnoy). *a* and *b*, River-valleys cut through Palæozoic rocks. *m*. Level of old deserted river-valley.

If the two channels *a* and *b* in this section represented the same valley taken on a loop line, the line *m* would represent a former channel excavated thus deep before the river was diverted into its present more circuitous route, and the original one abandoned.

Drainage Influences. The original direction of the surface-waters —that which regulated the subsequent flow of the rivers—would in the first instance depend upon the contours of the land, formed as it first emerged from beneath the sea, and afterward upon changes of level; at the same time, the directions of the joints of the strata and the occurrence of faults and fissures must, more or less, accordingly as the velocity of the water and the nature of the strata varied, have affected the course of the waters.

M. Daubrée has directed attention to the coincidence of the lines of joints with those of the rivers on the northern coast of France (Chapter xvi). In mountain-ranges the dislocations and fissures must have served from the first as water-channels. How far such causes may have affected and facilitated the incision of those wonderful river-channels (Fig. 29) with which we have of late years been made acquainted [1] in the high plateaux of

[1] The reader should consult the splendidly illustrated Survey works on the Cañons of Colorado by Professors Newberry, Hayden, Powell, Clarence King, Captain Dutton, and other State-Geologists,—works which the liberality of the American Government has made familiar to the geologists of Europe.

Colorado, seems to me a yet unsolved problem. The majority of American geologists ascribe, it is true, these deep and almost inaccessible gorges entirely to water-erosion, but still some of them allude to the possibility

FIG. 29.—*View of the Marble Cañon from the Vermilion Cliffs near the mouth of the Paria* (Powell). In the distance is the Colorado River. On the right are the Eastern Kaibab monoclinal folds, which further off pass into faults. The surface consists of Carboniferous strata. The Cañon is 65 miles long; in a direct line 20 miles less. At its head it is 200 feet deep, which depth increases to 3500 feet at its junction with the Colorado.

of the direction having been originally given by fissures on the surface. With regard to these Cañons, which are commonly adduced as typical

examples of what can be effected by the power of water-erosion combined with long geological time, the evidence on this point does not appear to me to be altogether conclusive, and I would venture to suggest a some what different interpretation for some parts of the process.

The Cañons of Colorado. That the action of the rivers and surface degradation have produced extraordinary results in this region is sufficiently clear. Rivers flowing through high table-lands in narrow channels a mile or more deep, and from 200 to 300 miles in length, present a phenomenon such as no other part of the world can offer, although some very remarkable instances exist in some parts of Africa and elsewhere. The present features are the result of two agencies: 1. River-erosion; 2. Weathering and degradation of the sides of the chasms. The effects of the latter vary according to the nature of the rocks. In some places the vertical walls of the cañons are prolonged to the surface; at others they present inclined slopes and the most fantastic forms, simulating towers, pinnacles, buttresses, etc., so admirably portrayed in the works of the American geologists. We have first however to consider the cañons merely with regard to river-erosion.

We cannot do better for this purpose than take a general view of one of those great cañons which presents the more simple form, and the one least complicated by weathering, such as that pictured by Professor Powell in his bird's-eye view of the Marble Cañon (Fig. 29).

The general effects of weathering will be considered in chapter ix. It will be sufficient for the present to show the contrast between the weathered sloped edges on the surface and the vertical chasm below in the following view of the Dolores Cañon.

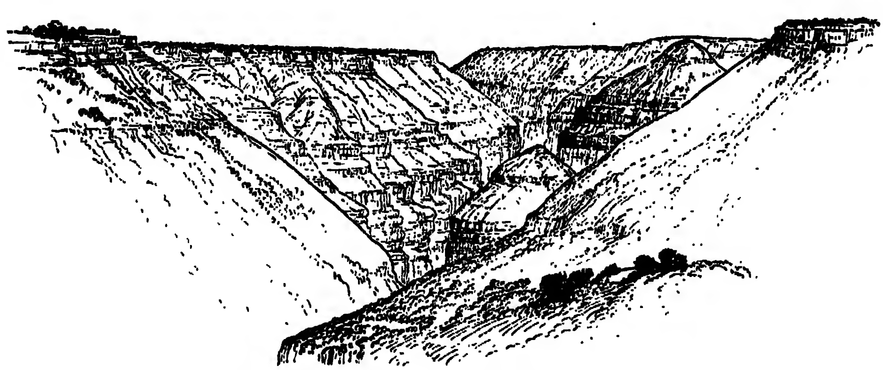


FIG. 30.—*A Glimpse of the Dolores Cañon, Colorado* (Hayden).

This cañon, which is a branch of the Grand River Cañon, is more than 2000 feet deep, and quite impassable. The walls below are so close together, that it is not possible to see the river from the top.

We may therefore eliminate the great upper slopes and all the remarkable sculpturing of the surface from the inquiry, and consider the cañons in relation to river-action only as vast vertical chasms extending directly from the surface to depths unequalled in any other part of the world. That they are not lines of fault have been sufficiently proved, inasmuch as the strata on either side of the cañons are on the same level. Further than this, the cañons traverse the plateaux irrespective of faults, folds, and of monoclinal escarpments, passing across the one and through the others without turning to the right or left; and the general belief is that the rivers had plotted out their channels before the country assumed its present surface configuration. Beyond this, one opinion is that the erosion proceeded more rapidly than the general erosion of the surface by rains and weathering, so that the depth of the cañons marks the difference between the progress of the river- and of the surface-erosion; but, as it is also stated that the latter has in places removed from 10,000 to 27,000 feet from the surface, it gives a depth of river-wear which requires further proof. Another opinion presupposes that the rivers being older than the folds, faults, and monoclinal lines which they traverse, the slow movements whereby these were formed progressively brought the strata within the action of the rivers, which sawed their way through the rising ground so rapidly as to keep pace with, and not be diverted by, the rise of the land.

The alternative to this view is that the land was first disturbed and elevated, and that in the process of elevation the surface was fissured and rent to great depths, these fissures forming, from the first, lines of drainage which have never varied. This view has been objected to, but there are some considerations that have, I think, not been sufficiently noticed, and which may remove some of the difficulties supposed to be fatal to it; or at all events, there are some modifications I would suggest that may be more in harmony with the existing phenomena.

In the first place, it is not necessary that a line of fissure should be a line of fault; nor is it otherwise than very rarely possible to detect a line of fissure, which at great depths may be nearly close, under the mass of débris and valley deposits, which, with few rare exceptions, cover valley-beds.

On the other hand, if a valley be excavated by river-action, traces of the presence of the water at the successive levels it occupied are commonly left at some spots, and I am not aware of any such high-level river-deposits having yet been pointed out by the geologists who have visited these marvellous scenes. The narrowness of the passes and the perpendicularity of the walls may in many places have left no room for such lodgment; but there are more open spaces where they could have been preserved. Nor am I aware that any old deserted river-channels in which the present rivers formerly flowed have been met with at high levels. Neither do the cañons

(as I have before mentioned) show that width on the surface which is usually the result of river-action before the rivers settle into a definite channel. It may be that the surface-erosion has removed all traces of this early stage of river-action, but this is difficult to imagine over an area so wide and presenting such a variety of conditions.

Abandoning lines of faults as against the evidence, there is still the possibility of rents and fissures having been formed in other ways, for lines of fissure are not to be confounded with lines of fault. The physical conditions of this great area are peculiar and abnormal. It forms—not a ridge or an isolated high plateau—but a vast dome-shaped mass, rising in the centre to the height of 12,000 to 14,000 feet. This form of surface may have produced lines of rent without faulting, or it may have so opened the joints of the rocks (see Chapter xvi) as to have produced a labyrinth of crevices along such lines of least resistance, amongst which those of primary importance would become the main lines of drainage. The peculiar direction and somewhat eccentric orientation of the chasms give, it seems to me, support to this view.

Yet, notwithstanding that the evidence is, I think, insufficient to assign the whole work to the one cause, it is impossible to resist the conviction, looking at the present force of those rivers, the rapid degradation of the rocks, and the vast depth of the chasms, that prolonged water-action has been the one main agent, although its operation may have been facilitated, the time shortened, and the magnitude of the work enhanced by the rents and fissures which were so likely to be formed in consequence of the strain to the surface caused by the great dome-shaped elevation of a 'massif' of rocks rising to the height of 12,000 to 14,000 feet.

One special cause of river-erosion in this case has been pointed out by the American geologists, which deserves attention. They have shown that the blocks and sharp sand, with which the rivers, or rather torrents, are charged during floods (and these now raise the level of the rivers 20, 30, or even 40 feet), have a powerful mechanical action on the sides and beds of the channels through which the rivers flow. But notwithstanding this 'corrosive' agency and the undoubted force of the rivers, the phenomena appear to me more in harmony with an original rending of the rocks—deep fissures and crevices being first formed—and that then the erosive river-action commenced in those fixed lines; for otherwise, with rivers of such power, it is scarcely probable that they would have kept within the very narrow limits of their present channels, especially during their first stages.

The vertical faces exposed by the fissuring and rending of the ground,—and extended to greater depths in certain of these channels by river-action,—have had the further result of exposing to subaerial action and enormous weathering adjacent areas where the surface was wedged open

only on the lines of joints, but still sufficiently so to admit of the action of meteoric agencies. The main drainage sought the larger and deeper fissures, receiving in its course contributions from all the minor tributaries furnished by the innumerable open joints, which, exposed to the action of the rain and weathering, gradually resolved the great rock masses into those labyrinths of simulated cyclopean ruins, which form so grand a feature in some portions of this wonderful district,—a feature as unique in its character as in its origin.

Marine Action. This wearing away of the land by rain and rivers of matter which is ultimately carried out to sea, is thus one source of the materials which have served to form sedimentary deposits; but another and equally efficient cause of denudation is the action of the sea on lines of coast by means of which great thicknesses of strata are planed down and removed.

Wherever hills fringe the coast they are eaten into by the sea and gradually worn back. This is owing to the incessant action of the waves beating on and undermining the land, which, as it falls, leaves vertical walls or cliffs; and also to the action, constantly repeated, of rain and frost, which breaks down and wears back the edge of the cliffs. The talus thus formed is more or less rapidly broken up by the breakers, and removed by the currents out to sea. This never-ceasing action, especially on coasts subject to the influence of any strong prevailing winds, causes the hardest rocks to give way in the course of time, and reduces fallen débris to sand and mud. Only the harder fragments resist destruction, but the same ceaseless wave-action wears off their sharp angles, and reduces them to rolled and rounded pebbles. In looking, however, at the shingle which now surrounds our coasts, it is necessary to distinguish between the effects of present and past action, and to apportion to each its share in this work.

Origin of the Coast-shingle in the English Channel. For example, the flint shingle skirting the chalk cliffs of Kent and Sussex is not to be ascribed merely to the breaking up of the layers of flint of the existing cliffs. Some portion of that shingle has no doubt been thus derived, but it is an extremely small portion. The greater part has been derived from the beds of flint-gravel which skirt the inland valleys and many parts of the coast. In this gravel the chalk flints are already reduced to fragments, and the only further change they have undergone, when washed into the sea, is the wearing off of their angles, and their conversion into more or less rounded pebbles. These pebbles are easily distinguished from those formed directly from the unstained flints out of the chalk, by the patching of brown and yellow staining, due to their original gravelly matrix, which they still retain, and by their less angular forms. Tertiary flint pebbles have also been commonly introduced either directly or through the gravel.

A considerable portion of the more pebbly shingle on the coasts of the Channel is also no doubt due to the old (raised) beach of Quaternary age, portions of which still at a few places fringe the land, and overhang the present beach. It is, for example, to the wreck of this old beach between Portland and the coast of Devon that is mainly due the great pile of well-rounded shingle forming the celebrated Chesil Bank. Elsewhere on the coast from Penzance to Dover the materials of the same old beach re-appear in the present beaches, not only adding to their mass, but introducing also materials incompatible with the action of existing tides and currents. Other therefore than present agencies have contributed to the formation of the masses of shingle we now find on our shores; and this shingle therefore is not a measure of the wear of the land in the existing period[1].

Wear of Coasts. The rate of wear of the cliffs depends on the hardness of the rocks, on the angle they present to the sea, and on the presence of land-springs. While on the hard rocks of our south-western coasts the sea makes but little impression, the soft Secondary and Tertiary strata of the south-east coasts are being rapidly worn away by a less turbulent sea. This is apparent by the way in which the old 'Raised-beach' (Fig. 31, *a*), just referred to, still fringes, with few breaks, the coasts

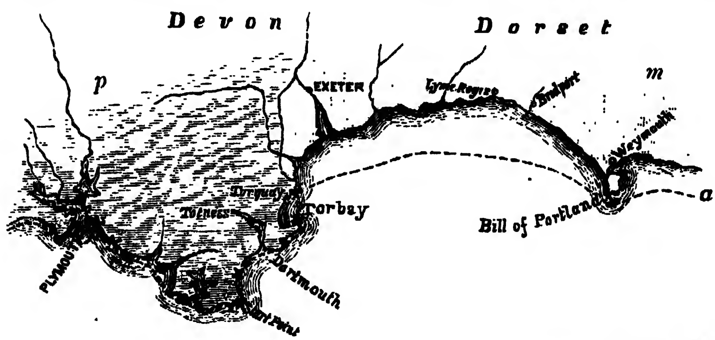


FIG. 31.—*Coast line of part of Devonshire and Dorsetshire.*— *m.* Mesozoic strata; *p.* Palæozoic strata.

of Cornwall, Devon[2], and South Wales, sheltered among the hard rocks which form those coasts, and following the various indentations and bays of the present shore,—thus showing how little the shore-line has changed since that late geological period.

On the other hand, along the Dorset coast the softer strata have within the same time yielded so much more easily to the action of the sea, that it is only at far distant intervals that any traces (×) of the old

[1] See the author's paper, 'On the Origin of the Chesil Bank,' etc., Minutes of Proceedings of the Institution of Civil Engineers, vol. xi. part ii. p. 4.

[2] The student will find very full information on this and other questions treated in this chapter, in Sir Henry de la Beche's 'Geological Observer,' London, 1851.

beach are met with. In the intermediate spaces deep bays have been formed by the wearing back of the land, like that between Torbay and Portland, where the sea has apparently encroached not less than eight or ten miles since the destruction of the old coast-line, *a*. If we adopt as a unit of wear the loss suffered by the coast of Cornwall and Devon since the period of the Raised Beaches (late Pleistocene), it will be evident that, notwithstanding this represents a very considerable length of time, the extent of wear has only been such as to indent here and there slightly the line of the original coast, and has left, even in some exposed positions, portions of the old beach pendant in the modern cliff. In fact the sea has only recovered so much of its lost territory as to remove the slope of the old-beach talus and eat back for a few yards the frontage of the solid rocks. And yet to show how ancient must be that part of the original

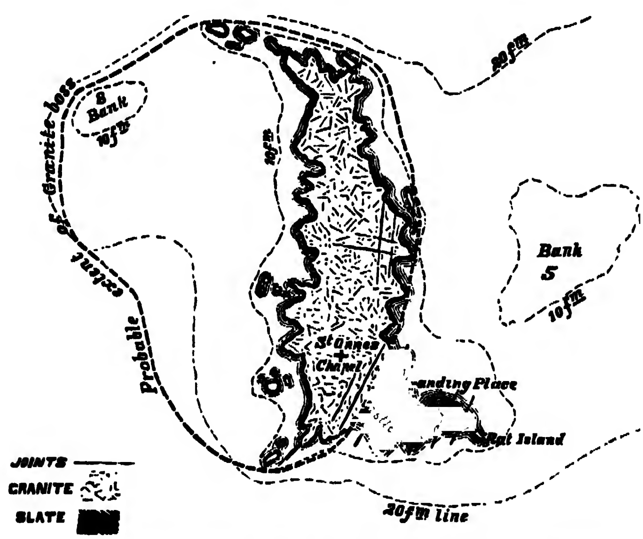


FIG. 32.—*Plan of Lundy Island* (after Whitley and the Survey Maps).

land, a fragment of it, consisting, as does the land in Cornwall, of a granite boss and surrounding slate, stands in the Bristol Channel at a distance of *ten* miles from the mainland of which it once formed part. What an insight does this remaining fragment give us of the antiquity of the original western land, when, instead of the loss of a few feet, or at most a few yards of coast, there has been here to all appearance a wearing-away, previous to the Pleistocene period, of a breadth may-be of nearly ten miles of the same hard rocks as those which now constitute the mainland of Devon and Cornwall!

The rapid wear of such soft strata as Chalk is well seen in the cliffs of Kent and Sussex, where the loss of land (when not protected) may average

from 1 to 2 feet a year [1]. Rents, at first small, commence on the top of the cliff, at short distances from its edge. These are gradually enlarged by the percolation of surface-water, and more especially in winter by the process of the freezing of water, until at last portions of the rock become detached and fall down, strewing the foot of the cliff with a mass of débris. A few weeks or months suffice for the sea to remove this débris, when the destructive action again recommences, and so goes on year after year.

The inland slopes rising at the back of these cliffs form but the remaining portion of hills which once stretched seaward. In some cases, as to the east of Brighton (Fig. 33), the cliff is cut through the outer slope of the hills. There *n* marks the present line of cliff and *nm* the prolonged slope which has been worn away.

FIG. 33.—*Diagram section across the coast east of Brighton.*—*a.* Elephant-bed (head or rubble). *b.* Raised beach. *c.* Present beach. *c.* Chalk. *n m.* Line of former prolongation of land.

Others, like Shakespeare's Cliff (Fig. 34) and Beachy Head, are formed on the inner slope of the hills, in which case it is evident that there has been higher ground, *nm*, seaward, and that it has been removed.

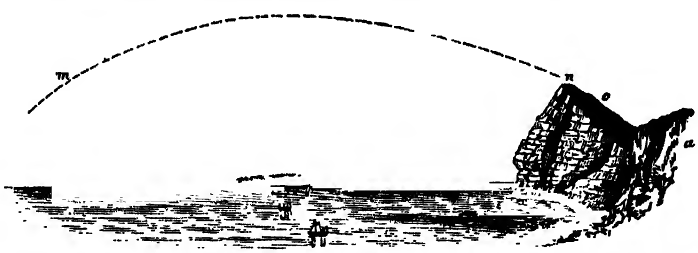


FIG. 34.—*Diagram section of the coast at Shakespeare's Cliff, Dover.*—*c.* Chalk cliffs. *a.* Lower cliff consisting of head and rubble. *n m.* Portion of land removed.

When the land first emerged from beneath the sea, it necessarily sloped down unbroken to the water's edge. In the cases last-named, we have therefore a mass of chalk at least 400 to 500 feet thick, and extending at least one, and more probably several miles from the present shore, removed by the action of the sea. The larger portion of this was no doubt removed before the time of the old Raised-beach, for traces of this beach exist on the opposite coast of the channel at Sangatte.

Evidence of this marine denudation may be seen at low tide at those places on the south coast where there is an absence of shingle and sand;

[1] According to an old map it would seem that at one place between Eastbourne and Beachy Head, the chalk cliffs lost between 1736 and 1844 about one-third of a mile, but the loss at Beachy Head is estimated to average less than a foot a year. At Kingsdown in the Isle of Thanet, the road a few years since passed along the edge of the cliff, fronting the small bay; now the road is washed away and carriages can no longer pass.

for the surface of the denuded Chalk left uncovered may sometimes be followed on a level plane from the foot of the cliff to and far beyond low-water mark (Pl. II, Sect. 1). In fact the chalk-bed off Dover extends across the channel. Effects of similar denudation on a vast scale at various geological periods will constantly come under the notice of the student in the field.

The soft sand and mud cliffs of the Eastern Counties have suffered still greater loss than the chalk coast; and the rate of wear has been more accurately recorded [1]. To mention only a few cases. Since the eleventh century the coast of Dunwich has been encroached on by the sea to the extent probably of not less than two miles. At Easton-Bavent, near Southwold, a breadth of 350 yards is stated to have been washed away by the sea in thirty-five years; and Captain Alexander has estimated the loss upon that coast generally at not less than seven yards annually. This rate, however, is very variable; and, while in some places, as at Mundesley, the cliffs continue to fall before the sea; at others, as just north of Lowestoft harbour, the sea has receded and left the cliffs some distance from the present shore.

Contemporaneous Organic Remains. The waste of these several coasts carried away to sea by the tides and currents mingles with the sediment brought down by the rivers, and they jointly form marine deposits composed of materials dependent upon the nature of the strata of the adjacent land, and on the distance from shore. However much these deposits may vary in composition, they all contain organic reliquiæ, or what in geology constitute 'fossils' of an analogous character; that is to say, identical with, and typical of, the life of the existing lands and of the surrounding seas [2]; for, with the sediment carried down by the rivers during floods, there are also carried down fragments of the trees and plants, together with the land-shells and the remains of animals swept from the surface which the waters have inundated, while the same sediment likewise entombs the marine organisms scattered over the sea-bed.

In Europe, owing to artificial protection, the quantity of land débris is small, but in less populous and more uncultivated countries, the destruction of vegetable and animal life is much larger, and the remains of these being carried out to sea, are there deposited with the remains of the shells, crustaceans, fishes, etc. inhabiting those seas, so that, if the sea-bed or deltas were now raised, the organic remains found in these modern sedimentary deposits would furnish the observer with the harder parts (such as the shells of the molluscs, the scales of fishes, etc.) of the marine fauna, while he would also obtain a certain amount of evidence with respect

[1] For many particulars of the destruction of this coast and elsewhere by the sea the reader should refer to Sir Charles Lyell's 'Principles of Geology,' vol. i. chapter xx.

[2] See Sir A. C. Ramsay, 'On Marine Denudation,' Mem. Geol. Survey, vol. i. p. 297.

to the adjacent land fauna and flora in the fragmentary remains brought down by the rivers.

Fossils typical of the Period. Thus in the earlier deposits in the estuary of the Thames there are found, together with the common shells now living on its marshy banks, remains of the red deer, wild boar, wolf, and other animals once roaming wild on the shores of that river, together with remains of the indigenous vegetation, such as the oak and the scotch pine, the poplar, the hazel, the yew, and a few other trees and shrubs.

The Ganges, on the other hand, still carries down on its waters carcases of buffaloes, deer, tiger, and the other wild animals of the country, together with the palms and other trees of tropical growth; and portions of all of these are entombed in the delta deposit, with the shells and fish remains of the adjacent seas.

So again the Mississippi transports tangled rafts of trees which it has uprooted from its upland shores; and these, together with portions of the fauna of the lands devastated by the floods, are carried down and deposited in the Gulf of Mexico, where they mingle with the more tropical forms of life living in that sea.

As we recede from the mouths of these rivers, the reliquiæ of the land brought down by them become scarcer; until ultimately in the deposits formed in the more open seas surrounding the continents there are only marine organisms to be found; so that while there are, at certain points, beds containing a land flora and fauna, alternating with others having a marine fauna, elsewhere over the larger sea or ocean areas there exist diverse synchronous deposits containing nothing but marine fossils. At the same time, the lithological character of the deposits varies from the coarse littoral to the fine deep-sea beds; while the thickness of the whole varies also according to the distance from land, the set of the currents, and the magnitude of the rivers.

Analogy with the past. In studying the various geological formations it must, therefore, be borne in mind that contemporaneous formations will differ greatly in their thickness, lithological character, and organic remains. But it must also be borne in mind that in the case of these modern sedimentary deposits all the organisms, whatever may be their local differences, are parts of animals and plants living on the globe at the present day; and, should these deposits be at some future period raised above the sea, the organic remains found in them will furnish a type of the fauna and flora of our period. It would also be possible, by the superposition of the beds, to show whether any changes in the fauna had taken place on the land within recent times: as, for example, in the estuary of the Thames, where the earlier or lower deposits of the estuary contain the remains only of the indigenous wild animals and plants and of savage man; whereas in its upper part there are found few of these remains,

but, on the other hand, the vestiges of a population of animals and plants belonging solely to an era of human civilisation.

It must also be remembered that, although the modern organisms differ so much in different geographical areas, still they all belong to allied living orders and genera, and that they all bear relation to the populations of the neighbouring lands and surrounding waters.

It is in a manner analogous to this that we are enabled to judge of past periods of the globe's history; for, as from early geological times there have ever been rivers, seas, and lakes, sedimentary deposits have always been taking place, just as they take place in recent times, so that the remains of the life of each successive period of the earth have been preserved to us in strata formed in the same way as at present; and, however fragmentary the remains may sometimes be, they must afford, it will be perceived, unerring types of the life of the respective geological periods. And, although the deposits have been from time to time raised so as to form dry land, and often again submerged, and the continuity of deposit, or of the geological record, has been interrupted during the period of emergence, still the formations built up during submergence are always in their relative order, and show not only the successive changes which have taken place in the life of each period, but also the order in which that life continuously altered and progressed.

It is thus that the analogy of the Present guides us in the interpretation of the Past; and it is thus by adhering to the rigid evidence of superposition and of organic remains that the weight and value of the evidence brought forward by the Geologist is made apparent and can be best realised.

CHAPTER VII.

THE FORMATION OF SEDIMENTARY STRATA, *continued*.

SOLUBLE MATTER ALWAYS PRESENT IN RIVER-WATERS. ITS ORIGIN. ITS CHARACTER AND QUANTITY. TABLE OF ANALYSES. THE THAMES. QUANTITY OF SOLID MATTER CARRIED DOWN BY THE THAMES. FORMATION OF CALCAREOUS STRATA. COMPOSITION OF SEA-WATER. SMALL PROPORTION OF CARBONATE OF LIME. ORGANIC ORIGIN OF LIMESTONES. MODERN CALCAREOUS BEDS. DEPOSITS IN LAKES.

Soluble Matter in River-waters. The extent to which sedimentary matter is carried down by rivers *mechanically* and visibly is, from what precedes, very evident. I purpose now to give some account of those substances which are carried down by the same rivers *in solution*, or invisibly, to the sea. Although, from the way in which this is effected, it does not, like the other, attract the attention of the casual observer, it is not the less important in its geological bearings.

Rain, which may be considered in the light of distilled or pure water, would, if it remained so, have no chemical action upon the strata which form a large portion of the earth's surface. For this object a supply of carbonic acid is required; and although this gas is present only in very small quantities in the atmosphere, it is being constantly generated by the decay of organic matter and other causes on land-surfaces, and taken up by the surface-waters. When therefore these ordinary waters come in contact with calcareous rocks, they dissolve the insoluble carbonate of lime, or rather convert it into the soluble bi-carbonate, which is then carried away in solution; and, as calcareous matter is a very common element in sedimentary strata, it is very rarely that carbonate of lime is not present in spring- and river-waters, together with any other earths or metallic oxides which may be acted on by the same solvent, or which are directly soluble in water.

Its Character and Quantity. The quantity of soluble matter carried down to the sea is as variable in different rivers as the insoluble matter, varying as in the other case with the character of the strata over which the rivers flow. For example, the Dee in Aberdeenshire, which flows over granite and slates with little that is soluble, contains only 3·12 parts of soluble salts in 100,000 parts of water; the Yonne in Burgundy, passing mainly over similar rocks, contains 7·7 parts, whereas the Rhine

and the Rhone, passing partly over crystalline and partly over sedimentary strata, contain respectively 17·12 and 18·2 parts; while the Thames and the Seine, flowing altogether over calcareous and argillaceous strata, contain the one 27·20 and the other 33·1 parts of soluble matter in 100,000 parts of water (see below). At first sight these quantities may appear inconsiderable; but when it is recollected how large is the volume of water which is steadily flowing to the sea, and that the matter in solution is a constant ingredient, always present in the river-waters, whereas the insoluble sediment is only carried down in floods, the importance of the fact will be apprehended.

The soluble ingredients generally present in river-waters consist of carbonate of lime, carbonate of magnesia, sulphate of lime, chloride of sodium, with smaller quantities or traces of alumina, silica, and iron. The proportions vary according as the rivers flow through a clay or a limestone country, or over sandstones or crystalline rocks. Carbonate of lime is, however, always one of the constituent ingredients in solution, usually forming from 60 to 80 per cent. of the total mineral matter present in such waters. Sulphate of lime, which is very slightly soluble, is also generally present, especially in rivers which flow over strata of Triassic and Tertiary age, in which gypsum or selenite is a common ingredient, as in the Trent Valley and the Paris Basin; and again, in a less degree, over clays containing selenite and iron-pyrites, as in the case of the Thames, which passes over large tracts of London- and of Oxford-clay, in which these minerals are always present. Carbonate of magnesia is soluble in the same way, but to a less extent than the carbonate of lime; and, as it is an ingredient present in small quantities in many limestones and in some clays and marls, and in larger quantities in the magnesian limestones and dolomites, magnesia enters sometimes in considerable proportions into the soluble matter of the river-waters. Iron also being present in some form or other in almost all rocks, very few river-waters are entirely free from it, generally in the state of the carbonate of the protoxide.

The following Table gives the proportion of soluble salts in 100,000[1] parts of different river-waters.

	Carbonate of lime.	Carbonate of magnesia.	Sulphate of lime.	Sulphate of magnesia.	Chloride of sodium, etc.	Silica, Iron, etc.	Total.
The Dee near Aberdeen	1·22	0.20	0·17	0·46	0·96	0.11	3·12
The Danube near Vienna	8·37	1 50	0·29	1·37	traces	0·89	12·42
The Rhine near Basle ...	12·79	1·35	1·54	0·39	0·15	0·9	17·12
The Rhone near Lyons	14·1	...	1·4	1·6	0·1	1·0	18·2
The Thames at Ditton	16·84	1·81	4·37	...	1·57	2·61	27·20
The Seine near Paris ...	17·4	6·2	3·9	1·7	2·5	1·4	33·1

[1] The imperial gallon weighs 70,000 grains, so to ascertain the proportion of salts per gallon, it is only necessary to multiply the above figures by 7 and divide by 10.

The Thames. To show how largely our rivers contribute to the supply of lime and other salts in the sea, and how much they remove from the land, the Thames may be taken as an example. The area of the Thames basin above Kingston is 3675 square miles, and from this surface the volume of water discharged by the Thames at Kingston never falls below 350 millions of gallons daily, while the mean daily discharge for the year is estimated at not less than 1250 million gallons. The water of the river, which derives its soluble salts chiefly from the Oolites and Chalk of Berkshire, Oxfordshire, and Gloucestershire, contains a quantity of solid matter in solution, varying from 25·55 to 32·95 parts, or an average, say, of 28 parts in every 100,000 parts of water, which is equal to about 20 grains per gallon. If we take from this 1 grain of organic matter, we have as a mean 19 grs. of dissolved inorganic matter for every gallon of water flowing past Kingston. This is, of course, apart from the sediment carried down in floods; and, while this latter is subject, as before mentioned, to very great variation, the quantity of matter in solution, whether in summer or in winter, in flood or in drought, varies but little throughout the year.

Taking therefore the mean daily discharge of the Thames at Kingston at 1250 million gallons, and the salts in solution at 19 grains per gallon, the average quantity of dissolved mineral matter carried down by the Thames every twenty-four hours is equal to 3,392,857 lbs., or to 1514 tons; or to 552,610 tons in the year. Of this daily quantity about two-thirds, or in round numbers 1000 tons, consist of carbonate of lime, and 238 tons of sulphate of lime; while limited proportions of carbonate of magnesia, chlorides of sodium and potassium, sulphates of soda and potash, silica, with minute quantities of iron, alumina, and phosphates, constitute the rest. If we refer a small portion of the carbonates, and the sulphates and chlorides chiefly, to derivation from the impermeable argillaceous strata, there will still be, we may assume, at least 10 grains per gallon of carbonate of lime, derived from the Cretaceous and Oolitic strata, over which the Thames flows, and the superficial area of which, in the Thames basin above Kingston, is 2072 square miles. Therefore the quantity of carbonate of lime carried away from this area by the Thames is equal to 797 tons daily, or 290,905 tons annually. This gives 140 tons removed yearly from each square mile, or 29,090,500 tons in a century, or equal to 14,000 tons from each square mile of surface. Taking a ton of chalk as equal to 15 cubic feet, this would amount to the removal of 210,000 cubic feet per century from each square mile, or nearly $\frac{1}{10}$ of an inch from a given surface of that extent in the course of a century, or 1 inch in 1000 years [1].

[1] The Author's Anniversary Address for 1872 in 'Quart. Journ. Geol. Soc.' See also Sir A. C. Ramsay's 'Physical Geology and Geography of Great Britain,' 5th Edit., chap. xxxii., 1878.

There is, however, reason to believe that a large, if not the larger, proportion of the calcareous matter removed by river-waters is derived not so much from the surface (although that is sometimes considerable) as from the interior of the hills through which the surface-waters percolate. Consequently, although the above estimate may give correctly the total quantity of carbonate of lime carried to the sea, it by no means follows that it gives a correct measure of surface-denudation. It may safely be reduced to one-half, if not to one-quarter, of that amount, or to ½ or ¼ inch in 1000 years. Really, however, such estimates are of little value, for not only are we unable to fix the relative proportions of removal of matter from the surface and from under ground, but we are ignorant of the relative importance of the rainfall at different geological periods [1]. We know nearly to a certainty that it was very much greater during the Glacial and Post-glacial periods than at present, but beyond that we can only surmise. Nevertheless it is evident that, although we have no exact measure, and that the effect of the rainfall in removing soluble matter from the surface of the hills is small, such action in the course of long geological time must have made its mark on the land, and is an important factor in the question of the denudation of calcareous strata and in the transport of lime-salts to the sea and great oceans.

Formation of Calcareous Strata. Connected with this removal of soluble matter by river-waters is the formation of marine calcareous strata. Sea-water, notwithstanding the quantity of carbonate of lime carried down by the rivers, contains much less lime than does river-water.

The composition of sea-water in all open seas (including the shallow seas around the British Islands) and the great oceans, is remarkably uniform, but differs in enclosed seas, as the following Table will show.

SOLUBLE SALTS IN 100,000 PARTS OF SEA-WATER.

	English Channel.	Mediterranean.	Black Sea.	Dead Sea.
Chloride of sodium ...	2705·9	2942·4	1401·9	11003
„ potassium	76·5	50·5	18·9	166
„ magnesium	366·6	321·9	130·4	1696
Sulphate of magnesia	229·5	247·7	147·0	233
„ lime ...	140·6	135·7	10·4	
Carbonate of lime ...	3·3	11·4	36·4	953
Bromide of magnesium	2·9	55·6	0·5	traces
	3525·3	3765·2	1745·5 *a*	14051. *b*

a. Exclusive of carbonate of magnesia .. 20·8
b. „ chloride of calcium .... 680. Silica etc.... 200.

[1] Still more are we ignorant of the different conditions of the atmosphere. There is reason to believe that at some former periods it contained larger proportions of carbonic acid than at present.

The 'Challenger' observations give as the mean proximate composition of 100 parts of ocean-water salts [1],—

Chloride of sodium	77·758
Chloride of magnesium	10·878
Sulphate of magnesia	4·737
Sulphate of lime	3·600
Sulphate of potash	2·465
Carbonate of lime	0·345
Bromide of magnesium	0·217

Forchhammer also found that the sea-water of the Atlantic contained silica in the mean proportion of 9 parts in 100,000 parts of water.

What becomes of the excess of carbonate of lime carried from the land into the sea? A larger proportion is elaborated from the water by the agency of fishes, crustaceans, molluscs, corals, etc., supplying the earthy material for the skeleton of the one, the shells of others, and the framework of the last [2]; while another portion is probably thrown down by precipitation or converted into the sulphate.

Organic origin of Limestones. In tropical seas the agency of corals in effecting this elaboration is paramount, and many geologists are of opinion that limestone rocks are the result entirely of organic growth—that is to say, that they consist entirely of corals, nullipores, molluscs, crinoids, foraminifera, etc., or of their débris; and that, while the mechanically formed conglomerates, sandstones, shales, and clays were accumulated near the shores, or at moderate distances from land, the limestones were built up by life-agencies in the more open seas.

This however may be questioned. There can be no doubt that great limestone masses are now built up by such means in tropical seas, as we shall show when describing coral islands. We have there clear evidence of the formation at the present day of limestones as solid and compact as those of the Carboniferous and Devonian series. We have also in the Chalk evidence of so vast a profusion of foraminifera, that in places they constitute almost the entire mass of the rock. But have all lime-rocks a similar organic origin? It is a *vera causa* so far as it goes, but there is often a large proportion of amorphous carbonate of lime in the calcareous strata to which it is difficult to assign such an origin.

The Lower Chalk, which has a considerable proportion of silica and argillaceous matter, contains in many places but little organic débris;

[1] The Challenger Reports, 'Physics and Chemistry,' by Dr. Dittmar, 1884.

[2] Bischof made some curious calculations on this subject. He found that as sea-water contains about $\frac{1}{10000}$ part of its weight of carbonate of lime, every oyster requires for the formation of its shell a quantity of water about 50,000 times its weight. Nevertheless the volume of water annually conveyed to the sea by the Rhine is so great that he estimated that this Rhine water would yield carbonate of lime enough to supply material for the shells of 332,539 million oysters. 'Chemical and Physical Geology,' vol. i. p. 80.

and foraminifera, though common in some localities, are so scarce in others that no traces of these microscopic fossils can be detected in some beds, which are mere masses of amorphous carbonate of lime, with a variable admixture of alumina, silica, etc. The amorphous chalky matter produced by the decomposition of coral rock, takes place only around and near coral reefs and islands.

Sorby, while advocating the organic origin generally of limestones, including chalk, admits that a *large part* of many limestones consist of fine granular particles, respecting which it is impossible to say whether they have been derived from organisms which can decay into granules, or from older rocks ground-down, or in some cases from carbonate of lime precipitated as granules as *some certainly must have been* [1].

As all calcareous matter must have been derived originally from the decomposition of alkaline and earthy silicates, we have either to suppose the elimination, from solution in sea- and lake-waters, of the total volume of calcareous rocks by organic agency, which is scarcely possible, or else that this process is supplemented by chemical reactions and precipitation. For the reasons before assigned, it is impossible now to compare the ocean-water, and the repeatedly-washed detrital matter subject to its action, with the earlier ocean-waters, when there was a greater extent of decomposing igneous rocks on the lands, and the surface-waters were surcharged with the products of decomposed silicates. The mere processes of elimination involve incessant change of conditions, and imply the operation of more active chemical action during geological periods than now obtains.

The presence of the large proportion of soluble silica in so many of the Cretaceous and Jurassic strata of itself indicates a very different state of things to any which obtains in the present seas. It shows that the quantity of soluble silicates carried down into the sea was at times very large, and consequently the reactions which ensued, owing to the liberation of the alkaline bases, are such as are likely to have led to the precipitation of some of the lime as an amorphous carbonate.

To enter into the discussion of the exact reactions which took place would here be out of place, but I may point out that the decomposition of the dissolved silicates might be effected by free carbonic acid, or by alkaline carbonates present in the waters, and, if salts of lime were present, its precipitation as a carbonate should ensue.

Dr. Sterry Hunt attributes the precipitation of the carbonate of lime to the reaction of carbonate of soda on the chloride of calcium, by which carbonate of lime is precipitated and chloride of sodium or common salt, which enters so largely into the composition of sea-water, is set free. The objection to this hypothesis is that it leaves the origin of the chloride of

[1] 'Anniv. Address, Geol. Soc.' for 1879, pp. 91 and 92. The italics are mine.

calcium itself unaccounted for; Dr. Sterry Hunt states, however, that he found the water which impregnates the great mass of calcareous strata, lying in Canada at the base of the Palæozoic series, charged with chlorides of calcium and magnesium with only a small amount of sulphates. This composition, he thinks, may represent that of the water of the Palæozoic seas, and hence by the reaction above named the chloride of calcium of the old seas has been gradually replaced by the common soda-salt of the present seas[1]. It is certain, however, that the chloride of sodium soon became common in the Palæozoic age, for in America strata both of Upper-Silurian and Lower-Carboniferous age contain extensive beds of salt.

Modern Calcareous Beds. The carbonate of lime held in solution in underground waters is a source of frequent calcareous deposits, either giving rise in springs, where it exists in excess, to the deposition of purely tufaceous beds or travertin, or else acting as a cement to quartzose sand and shell-beds, and thus forming local layers of calcareous sandstones and shelly limestones. The cementation of loose shell-sand and other matter by carbonate of lime is of very common occurrence on coasts where springs issue on the shore, or where land-springs force their way out at greater depths in the sea-bed in the manner described in Chapter x. In some places it appears due not so much to calcareous springs as to water charged with carbonic acid acting on the shelly sand, and, on the carbonic acid being afterwards set free, re-depositing the carbonate of lime.

On our own coast this rock-forming process is taking place on the shore at Perleze Bay, three miles west of Padstow. A considerable length and width of calcareous sandstones with recent shells have been also formed in this way on the shore of the Clyde at Ardoch below Dunbarton. It is taking place likewise on the coast near Ostend, and at many places on the shores of the Mediterranean and elsewhere. Some of the beds of the alluvium of the Po have been thus solidified, and the shingle on part of the coast of the Adriatic has been formed into conglomerates, so much resembling the conglomerate which lies at the base of the sub-Apennine marls, that they have been mistaken for it. Off Ancona and Rimini beds of sand are often consolidated to a considerable depth beneath the sea and distance from the shore. The same consolidation of shelly sands is of very common occurrence around many coral and other islands. Still, however much some of these beds may, in aspect and compactness, resemble old calcareous sandstones, oolites, and conglomerates, they are always to be distinguished from them by their containing remains of recent shells, with their colours generally preserved, and at times the remains of human industry[2].

[1] 'Chemical and Geological Essays,' ed. 1875, pp. 2, 11, 23, etc.

[2] The solid, shelly limestone in which the human skeleton (now in the British Museum) was found some years ago on the shores of the island of Guadaloupe was formed in this way. It has all

In some of the islands of the Canaries, where there are strong calcareous springs on the shore, oolitic beds are formed, which are said to be as well-marked as some of the old oolites of England and France, and to contain, like them, the débris of innumerable shells and other organisms. Darwin mentions a case in the Island of Ascension where the shell-sand on the shore had acquired so much solidity by the action of a calcareous cement that it is almost as heavy and as dense as marble. This cementation forms one of the processes, although only a minor one, by which some rocks have been consolidated. The formation of calcareous tufa will be described under the head of Mineral Springs (chapter X).

Lake Deposits. There is yet one other class of modern sedimentary strata to be noticed, namely the freshwater deposits formed in lakes. In lakes where the rivers carry down much sediment—in some of the Swiss lakes, for example—deltas are formed, as on sea-coasts, containing lacustrine freshwater remains; but in others, where little sediment is carried in, either deposits of peaty matter take place, or, where freshwater shells abound, beds of marl are formed; for the thin freshwater shells of lakes decompose readily, and turn into a white marl or chalk-like substance.

In 1817 Warburton drew attention to the number of freshwater shell-marls that there were in Fifeshire and Forfarshire, and to their relation to some of the freshwater limestones of Tertiary age in Europe[1]. Sir Charles Lyell gave a more detailed description of these deposits of peat, sand, and shell-marl in Forfarshire. He mentions that at one spot a pure shell-marl had been sunk through to the unusual depth of 16 feet. Horns of deer with tusks of wild boar were frequently met with[2]. Shell-marls have been also noticed and described by Buckland and Rupert Jones in the Valley of the Kennet, and by Hamilton in Cambridgeshire.

In some of the large lakes of America the myriads of decomposing shells have formed thick beds of white marls, in which only a few stray *Uniones*, *Planorbes*, and *Limnææ* have escaped destruction, so that, should they become hardened, they would form limestones very much like those of some of the great Tertiary freshwater formations of continental Europe.

Strata formed by Chemical Reactions. Besides the strata thus formed by ordinary sedimentation, there are others which are the result of subsequent change—not the change arising from metamorphic action at high temperatures, but from chemical reactions under the more ordinary conditions and temperatures of the time, and operating at or near the surface, or arising from the decay or change of constitution in organic

the appearance of an old-rock fossil, but the embedding rock has been shown to be a limestone still in progress of formation, and it appears that these human remains are probably not more than about two centuries old.

[1] 'Trans. Geol. Soc.,' vol. iv. p. 305.

[2] 'Trans. Geol. Soc.,' 2nd ser., vol. ii. p. 73.

matter. The more important of these substances are Gypsum, Rock-salt, Dolomites, and Coal. The last will be discussed when we come to speak of the Coal-measures; and the mode of formation of rock-salt and gypsum will be more fully described in the chapter on the New Red Sandstone. We shall here merely consider some of the chemical reactions to which they owe their origin. With respect to dolomite the case is different, for although these rocks are due in some cases to powerful metamorphic action, in others their origin is certainly a consequence connected with original sedimentation; while one form of dolomite has clearly been caused by a process of change or replacement in the original rock dependent upon causes acting externally, or epigenesis.

Magnesian Limestones. It cannot be asserted, as in the case of so many limestones, that these are an organic product, for molluscous shells consist almost entirely of carbonate of lime, and Corals, with few exceptions, have the same exclusively calcareous composition. A few of the latter contain 1 to 2 per cent. of magnesia, but only one species was found by Forchhammer to contain as much as 6 per cent. of carbonate of magnesia. Whatever doubt there may be about ordinary limestones being sometimes the result of precipitation, there can be none that the magnesia present in others is due to direct sedimentation or precipitation. A large number of marls and limestones contain a small percentage of magnesia, while in others of these rocks it amounts to as much as 30 or 40 per cent., or more. According as the proportion increases and the combination with the lime is more intimate, the rocks are classed as magnesian limestones or as dolomites.

FIG. 35. *Section of a Limestone Quarry near Kilkenny* (A. Wyley)[1].
a. Unaltered limestone. *b.* Dolomitised limestone.

But there are also instances in which it is certain that the rock originally consisted of carbonate of lime only, and that the change has been of subsequent date, nor was caused by ordinary metamorphic action. Some very interesting instances of the conversion of shelly limestones into true dolomites by an alteration subsequent to the formation of the original rock have been recorded by the Irish geologists. In

[1] 'Journal of Geol. Soc. of Dublin,' vol. vii. pp. 115, 122.

Kilkenny the Carboniferous Limestone is often altered into dolomite, the lower part of a section showing ordinary limestone with the usual fossils, whereas in the upper part of the section the limestone is replaced by a gritty dolomite with the fossils and stratification obscured or destroyed. There is no passage. The transition from one to the other is abrupt and irregular.

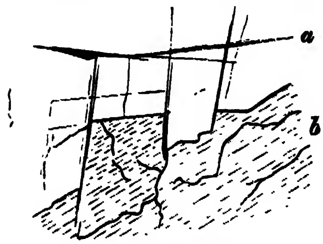


FIG. 36. *Ground-plan showing the junction of the limestone and its dolomitised beds near Stoneyford, Co. Carlow* (A. Wyley).

Both in the section (Fig. 35) and in the ground-plan (Fig. 36) the alteration proceeds, independently of the bedding, from the surface and along the lines of joints, against which it frequently stops suddenly.

Similar instances were observed by Professor Harkness in the Carboniferous Limestones of Cork[1]. There also the structure of the limestone is altered, and the fossils are obliterated or the shells removed, while it is clearly evident that the alteration has been effected from above downwards.

No very satisfactory explanation has been given of the manner in which this alteration has been caused. The experiments of Morlot and Marignac, and of Charles St.Claire Deville[2], are very suggestive; and, supposing heat to be equivalenced by increased pressure, it is conceivable that long exposure to sea-water at certain depths may, by the reaction of the salts of magnesia in solution on the limestone, have effected the substitution. The former on heating carbonate of lime in a close vessel to about 200°C., and under a pressure of 15 atmospheres, with a given proportion of sulphate or chloride of magnesium, obtained by double decomposition a mixture of carbonate of lime and of magnesia in proportions constituting dolomite.

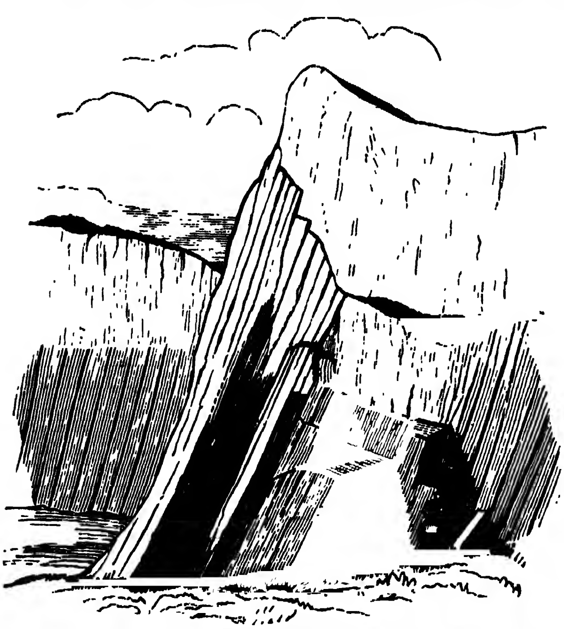


FIG. 37. *Section of a dolomitic Carboniferous Limestone near Cork* (Harkness).—The lower part consists of yellow dolomitised limestone; the upper of light-coloured unaltered limestone.

[1] 'Quart. Journ. Geol. Soc.,' vol. xv. p. 86. [2] 'Comptes Rendus,' vol. xxx. p. 89, 1858.

The latter saturated a piece of chalk with a solution of chloride of magnesium and subjected it in a platinum crucible to a heat a little over 100° C., when a certain amount of chloride of calcium and carbonate of magnesia were formed. Washing the chalk to remove the chloride, and again saturating it with the magnesian salt, another portion of magnesia was taken up; by repeating the process a saturation of 1 : 2 was obtained, the proportions in dolomite being 1 : 1.5. A madrepore subjected to the same process underwent the same change without losing form. Similar results were obtained by using sulphate of magnesia. Other chemists have suggested that water holding a slight quantity of carbonate of magnesia in solution might cause the alteration.

On the other hand, it is easy to conceive the formation of dolomitic strata by sedimentation; for, as we have before shown, the magnesian silicates, serpentine especially, must by their decomposition have furnished both salts of magnesia and of lime. Professor Sterry Hunt[1] supposes that the carbonates of these earths were formed by the reaction of the carbonate of soda, resulting from the decomposition of felspathic rocks, upon chlorides of calcium and magnesium present in the old sea-waters. This first separates out the lime, and on further saturation the hydrous magnesian carbonate is deposited. Another suggestion is that the bicarbonate of lime, added to a solution of sulphate of soda or sulphate of magnesia, gives rise to bicarbonates of these bases together with sulphate of lime, which latter is soon thrown down when in slight excess.

Gypsum and Rock-Salt. Magnesian marls and limestones are so constantly found in association with anhydrite, gypsum, and rock-salt, that all these substances have long been supposed to be the conjoint products of chemical reactions in which they have severally had part. The red marls of the Trias contain beds of gypsum or alabaster alternating with beds of rock-salt; and magnesian marls and beds of gypsum exist in close association in the Upper-Tertiary strata of the Paris basin and elsewhere. The rock-salt and gypsum form lenticular masses, or else penetrate the enveloping strata in strings and veins. Sulphate of lime may, as just mentioned, be product of the reaction of bicarbonate of lime on sulphate of magnesia. It readily separates out from highly saturated waters, such as exist in a salt lake or enclosed sea subject to excessive evaporation, after which the chloride of sodium or common salt is thrown down. In such saturated solutions as the Dead Sea precipitation of both these substances takes place. Of the thickness or order of the deposits there, however, we have no knowledge.

In the Triassic and Tertiary formations these substances occur in vast masses forming beds from 1 to 100 feet or more in thickness; in the remarkable case of the artesian well at Sperenberg the bore-hole passed

[1] 'Chemical and Geological Essays,' 1875, pp. 80, 90.

through 283 feet of gypsum and anhydrite, and 3769 feet of rock-salt. Although, therefore, we may form some notion of the chemical reactions which led to the deposition of these beds, it would seem that the conditions under which they were effected must have been very different from anything of which we have any experience.

Gypsum is sometimes produced by the action of the underground waters on anhydrite, or by hydration. A very curious phenomenon results from this change. As the water of hydration in gypsum amounts to more than 20 per cent., when the anhydrous sulphate of lime passes into the hydrated sulphate a great increase of bulk takes place, and this is effected with a force analogous to that of freezing water. Such is the underground force, that the anhydrite will under these circumstances lift masses of strata into dome-shaped hillocks, sometimes of considerable size. Some instances have been described, in which the enclosing strata are thrown up vertically, or are even reversed, by the sides of the mass of gypsum [1].

Gypsum is also in some cases produced by the action of sulphureous spring waters on limestones.

In the minor case of the selenite crystals in the London, Kimmeridge, and other argillaceous strata, this mineral results from the decomposition of the sulphide of iron and its reaction on the carbonate of lime dispersed through the clays; the sulphide of iron, by absorbing oxygen from the water of imbibition, is converted into the sulphate of the protoxide of iron, which in its turn is decomposed by the bicarbonate of lime, giving rise to sulphate of lime and carbonate of iron. The former segregates and crystallises out in the form of crystals of selenite, while the iron sometimes passes into the state of the peroxide, or at others is removed.

Thus sedimentary strata may be formed—

1st. By rivers transporting matter, mechanically or in suspension, into estuaries and open seas, to which is superadded the débris derived from the wear of the coast-lines.

2nd. By the salts of lime, together with smaller proportions of magnesia, etc., carried out in solution by rivers to the sea, and there separated from the sea-water in part by the agency of living organisms, and in part by chemical reactions and precipitation.

3rd. By lacustrine deposits, and by the formation of calcareous beds arising from the disintegration of shells in freshwater lakes.

4th. By chemical reactions and by epigenesis.

There remain for consideration the deposits formed in the more open and deep seas.

[1] Elie de Beaumont, 'Explic. Carte Géol. de France,' vol. ii. p. 89.

CHAPTER VIII.

LITTORAL AND DEEP-SEA DEPOSITS.

NATURE OF THE SUBJECT. DEPOSITS IN LITTORAL AND SHALLOW SEAS. THE ENGLISH CHANNEL. SHINGLE-BANKS. WAVE-, CURRENT-, AND TIDE-ACTION. FALSE BEDDING. WESTERN COAST OF FRANCE. DEPOSITS AT GREATER DEPTHS. OCEAN-CURRENTS. BABBAGE'S LAW. THE 'CHALLENGER' EXPEDITIONS DEEP-SEA SHORE-DEPOSITS. OCEANIC DEPOSITS. GLOBIGERINA OOZE. RADIOLARIAN OOZE. DIATOMACEOUS OOZE. RED AND GREY CLAYS. MANGANESE. DISTRIBUTION OF THE DEEP-SEA FAUNA. FORAMINIFERA; SPONGES; CORALS; ECHINODERMATA; CRUSTACEA; MOLLUSCA; FISHES; TEETH AND EAR-BONES. STERILE AREAS. SURFACE AND DEEP-SEA POPULATION. NO EXTINCT GENERA RECOVERED. PLIOCENE SPECIES DISCOVERED. THE NORWEGIAN SEAS. OCEAN CIRCULATION AND TEMPERATURE.

AS the delta-deposits described in Chapter VI are in the course of time raised above the sea-level and converted into dry land, it becomes an easy matter to investigate their structure. There are, however, other sedimentary deposits, now also in process of formation, but at a distance off-shore and at depths in the ocean where we cannot ascertain the thickness of the sediments, or what may exist beneath the sea-floor. But even this superficial examination of the sea-floor is of great value, as it shows the extent of distribution of sedimentary materials, and the range of life, over areas far distant from the land.

The subject divides itself into two parts: (1) Those littoral deposits at moderate depths, which extend beyond the deltas, and subtend the *littoral zone* below low water, down to depths of 800 to 1000 feet. (2) The deposits spread over the ocean-bed, away from direct shore and river-action, at great and abyssal depths. For a knowledge of these latter we are mainly indebted to the important expeditions that have been so successfully carried out during the last fifteen years. The valuable work done by Dr. Carpenter and the late Dr. Gwyn Jeffreys, in connection with the voyages of the 'Lightning,' 'Porcupine,' and the 'Valorous,' and by the several biologists and chemists in connection with the longer voyage of the 'Challenger,' together with similar important deep-sea researches made during the same period by the Austrian, German, French, Italian, American, Swedish, and Norwegian naturalists, have made us acquainted with new ground and a new world of life, of which previously we had only dim though striking glimpses. We can, however, only look at these most interesting

results in their stratigraphical bearings; those who wish for further information on the subject should consult the various papers of these authors, published during the last twelve years in the Proceedings and Transactions of the Royal and Zoological Societies; the Annals and Magazine of Natural History; the several Reports on the voyage of the 'Challenger;' together with the works hereafter referred to.

The English Channel. For the shallower seas we should refer to the late Mr. Godwin-Austen's[1] excellent account of the Valley of the English Channel, and to M. Delesse's[2] description of the sea-bed of the coasts of France and of countries adjacent. As a rule, long well known to navigators, the materials forming the sea-bed become finer as the distance from land and the depth of water increases; but Mr. Godwin-Austen showed that, while quartzose and shelly sands are spread over the greater part of the Channel, there are also large irregular tracts of angular, sub-angular, and rounded shingle. These shingle-beds extend as far as the entrance of the Channel in long. 10° W., where they are found at depths of 500 to 600 feet.

So exceptional a distribution is evidently not to be attributed to the present set of the tides and currents, but must be due to some anterior configuration of the surface; for the coarse shingle is found far from land and beyond zones of sand, where, had it been drifted by currents, the fragments would hardly have retained their angular and subangular forms. Mr. Godwin-Austen accounts for this exceptional condition of the Channel-bed on the supposition that it was a former area of dry land gradually submerged, and that the zones of rounded shingle represent the successive coast-lines; in confirmation of this, he points to the fact that far out in mid-channel, and at considerable depths, he found perfect though decayed littoral shells, such as *Patella vulgata*, *Littorina littorea*, etc., and shell-sand formed on a shore-line. The submerged forests in the shallower parts of the Channel may be connected with these changes.

This explanation will account for the rounded shingle and shell-sand, but not for the *subangular* gravel and the *angular* fragments of granite, some of considerable size, found at depths of from 50 to 100 fathoms, and at distances of from 200 to 300 miles from land. These remarkable masses of débris, which stretch at intervals from fifty miles south of the Irish coast to the Little Sole Bank in long. 10° W., may be, as I have before suggested, part of the terminal moraine of the great ice-sheet which descended in the Glacial Period from the high lands of Scotland and Wales[3].

Tide and Current Action. Eliminating these coarser materials due to former causes, much of which no doubt has been and is still being

[1] 'Quart. Journ. Geol. Soc.,' vol. vi. p. 69, and vol. vii. p. 118; see also the Admiralty Charts.
[2] 'Lithologie des Mers de France,' etc., 1871.
[3] 'Phil. Trans. for 1879,' vol. 170, p. 691.

silted over by the tides and currents, let us now consider the effects to be attributed to these latter agencies alone.

The action of the waves extends to a depth dependent mainly on the slope of thesea-bed, and its effect is to spread the shore shingle over the marginal zone to certain variable depths. It is estimated that in the Bay of Biscay the action of the waves in ordinary weather does not extend beyond ten to fifteen feet, and in storms to about thirty-five feet. Off Portland, waves are said to move shingle at a depth of fifty feet; and, according to Sir H. De la Beche, at ninety feet off the coast of Cornwall. The slighter movements, such as may displace sand, extend however much deeper. According to Cialdi, as cited by Delesse, these may go on in the Channel to depths of 130 feet, in the Mediterranean to 165 feet, and on the more open coasts of the ocean to a depth of 650 feet; while ripple-marks, due to the same cause, are found not only in shallow water, but are said to occur at depths of above 600 feet.

The great agents however in spreading and carrying to a distance the materials borne down by rivers, formed on shore-lines, are the currents which traverse all seas (especially strong in the shallower seas) and tidal currents which run in places with great force. The former carry the sedimentary matter in one given direction, the latter move it backwards

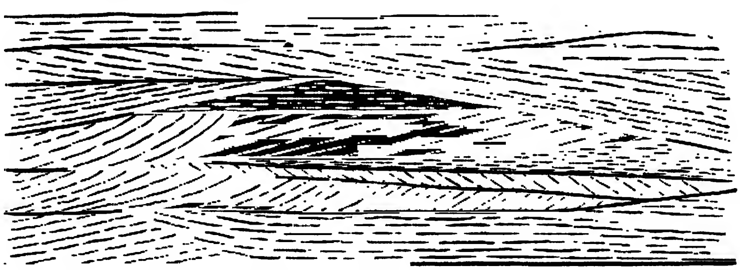


FIG. 38. *Section of a Coralline-Crag pit, Gedgrave, Suffolk, showing oblique lamination or false bedding.*

and forwards. The lighter materials are thus kept for a long time in motion and undergo an amount of wear, and a process of sifting and sorting, which gives uniformity to the deposit over areas more or less wide. Shifting banks of this kind, lying off the Bill of Portland, where the movement of the waters is felt to a considerable depth, are found to be in a state of incessant unstable equilibrium, moving with every ebb and flow of the tides. Generally, the action is only strong enough to move sand and shells, but there are places where the current is sufficiently strong to move rounded shingle. When the wave-action, tidal currents, and ordinary currents act in conjunction, the scouring and denuding become extended in proportion; banks are removed and channels excavated; and it is thus that a coast, which is undergoing marine denudation, may have deep-water channels formed along its marginal line, in place of the

gradually sloping and shallow soundings left by the encroaching sea on other coasts where this action is not so strong.

These are the causes that have given rise to that peculiar structure of the strata termed *false bedding* or *oblique lamination*, so common in many strata, especially in the Old and New Red Sandstones, the Suffolk Crag and others, of which two instances are given in Figs. 38, 39. Banks have been formed; their upper beds removed by a change in the direction of the currents, and the removed materials thrown over their sloping sides. Adjacent banks arise, and these in their turn furnish materials which on similar removal have been tilted over into the intervening shallows, or spread over the remaining base of older shoals, and thus a succession of beds, some horizontal and others with laminæ dipping in various directions, have been formed.

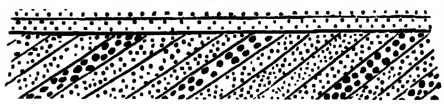


FIG. 39. *Section of the Pebble Beds of the Woolwich- and Reading-Series, in the railway-cutting, Bickley, Kent, showing alternate oblique and horizontal lamination.*

The Coast of France. The maps and observations of M. Delesse show that the sand and shingle of the English Channel extend also in a variable band along the western coast of France, as far south as the river Adour, to depths of 300 to 400 feet beyond the marginal shingle-zone. Beyond this zone is a sandy and gravelly silt, of unequal width, extending to further depths of 400 to 600 feet. These are more or less local, but the zone of quartzose and shelly sands which occupies other portions of the Channel is more widely spread, and at its entrance forms a zone ranging along the French coasts outside the two preceding zones, and extending in some places to a depth of 1300 feet. Beyond this zone is an argillaceous silt, with much amorphous silica, and variable proportions of lime and alkalies. This does not appear to extend into the English Channel. It skirts the French and Spanish coasts, which it approaches in places to within depths of 300 feet. In the Mediterranean it comes still closer to the coasts, and extends thence to all depths. It occurs in like manner in the Black and Caspian Seas.

The distribution of the fauna over the shore and littoral zones is described in minute detail by M. Delesse. Shells are almost everywhere common. They abound especially off granitic coasts; and great banks of them extend from the coast of Brittany to Cornwall. On the French coast oyster-beds extend from the sea-level to a depth of 230 feet.

It is not necessary, however, to dwell upon the distribution of this shallow-sea fauna, which is well known, further than to give a few results which may be useful to the geologist as points of comparison. In 1860 the late Dr. Gwyn Jeffreys estimated the total number of the Mollusca in the British seas within soundings at 598 species. Of these, he considered that about eighty species were confined to the seas of Shetland,

eighty to the intermediate area, and eighty-one to the British Channel; and that, of these latter, fourteen species were restricted in their range north to the shores of the Channel Islands. He has further shown that of about 800 marine Mollusca known in the European seas in 1872, and of the 290 species found in the seas of North-eastern America, 134 species are common to the two areas[1]. He afterwards informed me that, with respect to the deeper-water Mollusca in the same areas, the proportion of those which are common to the seas adjoining the United States and to the European seas is very much greater than in the case of the shallow-water species.

Deposits at greater depths. The preceding remarks apply only to those shore or littoral deposits, which are limited to depths not extending beyond the 100- and 200-fathoms' lines. These deposits, though generally restricted to within a distance of not over 150 miles from land, are shown by the 'Challenger' observations to extend to much greater depths than was before supposed. In fact, they do not seem to be limited by depth, but by distance from land. They were found at all depths from 50 to 3000 fathoms, merging eventually, as they recede from the land, into the various oceanic oozes and the Red Clay which occupy the rest of the oceanic basins.

It is evident that at these greater depths and greater distances from the land other causes than those under which the shallower-water deposits are formed must be in operation. The currents produced by the discharge of the great rivers, and the strong tidal currents, diminish in power with the distance from land and increase of depth. These more local forces there give way to the action of those great currents, which, if sometimes of less velocity, are of more imposing dimensions and length, and have a wider transporting power.

Some investigations of the late Mr. Babbage show how the distribution of finely-suspended matter may be affected by the action of currents of certain length and strength. He supposed a river 100 feet deep at its mouth, and carrying down triturated particles of four different degrees of fineness into a sea having a uniform depth of 1000 feet, and falling respectively 10, 8, 5, and 4 feet per hour. The distances to which under these circumstances the separate deposits formed by a marine current of given velocity would extend, are as follows[2]:

Relative size of particle.	Velocity of fall per hour.	Nearest distance of deposit to river.	Length of deposit.	Greatest distance of deposit from river.
1	10 feet	180 miles	20 miles	200 miles
2	8 ,,	225 ,,	25 ,,	250 ,,
3	5 ,,	360 ,,	40 ,,	400 ,,
4	4 ,,	450 ,,	50 ,,	500 ,,

[1] 'Reports Brit. Assoc.,' 1865, 1866, 1867, 1868.

[2] 'Quart. Journ. Geol. Soc.,' vol. xii. p. 367.

If this be the case for a depth of 1000 feet, what may not be the distance of transport effected in depths of 10,000 to 20,000 feet or more by those powerful currents which traverse the great oceans for thousands

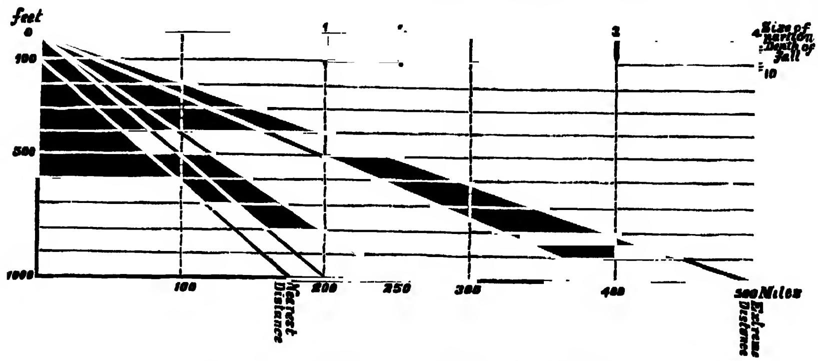


FIG. 40. *Diagram to illustrate Mr. Babbage's Table.*

of miles and in all directions? No part of the ocean-bed would be beyond the reach of transport of fine detrital matter; and this, judging from the 'Challenger's' observations, appears to be the case.

The Deeper Shore-Deposits. Mr. J. Murray states[1] that beyond the littoral zone, even in deep waters near the coast of most of the great continents and islands, a 'shore-deposit' extends for a distance of about 150 miles. In depths of from 100 to 700 fathoms this deposit consists commonly of mud of a green colour, due to the presence of an amorphous clayey matter with particles of green glauconite. Beyond 700 fathoms the clay is usually of a blue or dark-slate colour, and more compact and tenacious. On the east coast of South America it is of a red colour. Particles of mica, quartz, and other minerals are found in all these deposits, the particles increasing in size as the deposit approaches the land and passes into the littoral shingle-zone.

Near volcanic islands the shore-deposit (which round Hawaii extends to a distance of 200 miles from land) is less argillaceous, and is generally of a grey colour, owing to the presence of pieces of pumice, scoriæ, and dark volcanic sands: while around Coral islands there is a deposit of light-coloured coral-mud, which assumes shades of red as it gets into deeper water,—in places extending to 2500 fathoms. Near the southern ice-barrier a blue mud was found, containing many granitic and other pebbles, and blocks mostly rounded.

Oceanic Deposits. Beyond these limits of distance from land, and north of lat. 50° South, there was found, at depths in the open ocean varying from 250 to 2900 fathoms, but usually not extending below 1800

[1] 'Preliminary Report on work done on board the "Challenger,"' 'Proc. Roy. Soc.,' vol. xxiv. p. 518, *et seq.*

fathoms, a fine ooze, to which, from its being largely made up of one minute foraminiferal species, the term **Globigerina ooze** has been applied. This remarkable deep-sea deposit consists of a fine light-coloured silt or ooze, more or less calcareous, and generally abounding with the minute shells of foraminifera, chiefly *Globigerina*. Sometimes it is of a cream-white, at others of a rose colour, or else red or dark-brown. In some specimens there are numerous remains of siliceous Radiolaria, Challengeriæ, and Diatoms, but in others they are entirely wanting. In a few instances the shells are, as it were, run together by a siliceous cement. Sometimes, on the other hand, the base of the ooze seems to consist chiefly of soft amorphous matter; but even this often really consists of impalpable microscopic *Coccoliths* and *Rhabdoliths*[1]. Whenever the depth of the Atlantic increases from about 2200 to 2600 fathoms, this ooze, which Sir W. Thomson calls 'the modern chalk of the Atlantic,' passes into a red clay[2]. The following two out of the many analyses given will serve to show that this ooze has a very variable chemical composition. The proportion of carbonate of lime varies from 50 to 80 per cent.

	No. 1. Lat. 21° 57′ N., Long. 43° 29′ W. Depth 2025 fathoms.		No. 2. Lat. 18° 40′ N., Long. 62° 56′ W. Depth 1420 fathoms.	
Carbonate of lime ...	43·93	80·22	80·69[3]	Soluble in hydrochloric acid 92·75.
Sulphate „ ...	1·37		0·41	
Phosphate „ ...	traces		2·41	
Carbonate of magnesia ...	1·94		0·68	
Alumina ...	19·24		4·42	
Iron-peroxide ...	13·74			
Silica ...	0·00		4·14	
Insoluble silicates, silica, etc. ...	10·98		3·45	
Loss in ignition ...	8·80		3·80	
	100·00		100·00	

No. 1. This specimen contained many pelagic Foraminifera, belonging to Globigerinæ, Orbulinæ, Pulvinulinæ, Sphæroidinæ, and Pulleniæ; many Coccoliths and Rhabdoliths; and much amorphous clayey matter, with iron and manganese peroxides.

No. 2. The same Foraminifera as in No. 1, only a few Coccoliths and Rhabdoliths, and many shells of Pteropods and Heteropods; also otolites of Fishes and spines of Echinoderms, and a few siliceous spicules; some amorphous mineral matter with particles of quartz, felspar, hornblende, and magnetite.

Radiolarian Ooze. This is a deposit which has been met with only in the western and middle Pacific. It extends deeper than the Globigerina ooze, and was even found in one of the deepest soundings (4475 fathoms). It consists of a small proportion of amorphous matter with siliceous skeletons,—the exuviæ of Radiolaria, and a few Diatoms. It is of a light colour, but tinted red in places by the oxide of manganese.

[1] 'Proc. Roy. Soc.,' vol. xxiv. p. 533.

[2] 'The Voyage of the "Challenger,"' vol. i. p. 226.

[3] This is the largest proportion of carbonate of lime in any of these analyses.

Diatomaceous Ooze. South of the latitude of the Crozets, the last-mentioned ooze is replaced by an ooze made up of Diatomaceæ. Near the north edge of the Antarctic ice this ooze, which is light-coloured, is composed principally of the frustules and débris of Diatoms, with a good many Radiolarian remains and a few Globigerinæ. It was found in depths of from 1260 to 1950 fathoms.

Red and Grey Clays. These are by far the most abundant oceanic deposits. The clays are of grey, red, or dark-chocolate colours, and are found at depths greater than 2000 fathoms. The colour is due to the presence of iron and manganese oxides. These clays consist of fine amorphous matter, with larger particles of quartz, mica, pumice, scoriæ, manganese oxide, and other minerals; they are supposed to be derived in greater part from the decomposition of volcanic felspathic minerals. In some of the clays, microscopic siliceous organisms (Radiolaria) occur in great numbers.

The red clay itself is exceedingly fine, and remains for days, looking like chocolate suspended in the water. Its composition is variable, as the following two analyses show[1]. The $CaO.CO^2$ varies from 2 to58 per cent.

		No. 1. Lat. 22° 45′ N., Long. 40° 37′ W. Depth 2575 fathoms.	No. 2. Lat. 18° 56′ N., Long. 59° 35′ W. Depth 2975 fathoms.	
Soluble in hydrochloric acid, 72·59 parts.	Silica	12·22	26·00	56·83
	Alumina	5·61	12·28	
	Iron-peroxide	4·65	11·44	
	Carbonate of lime	51·16	3·50	
	Sulphate „	1·02	1·47	
	Phosphate „	0·00	traces	
	Carbonate of magnesia	1·93	2·14	
Insoluble 14·28 parts.	Residue of alumina Iron-peroxide and silica	14·28	35·72	
	Loss in drying	9·13	7·45	
		100·00	100·00	

No. 1 is a deep red amorphous clay, with many particles of felspar, augite, mica, quartz, magnetite, etc.

No. 2 is an amorphous clay, with iron-peroxide, small particles of hornblende, augite, sanidine, quartz, magnetite, and a few grains of manganese peroxide.

This extensive deposit of red clay, covering a large portion of the ocean beds, is one of the most interesting facts brought to light by the researches of the 'Challenger.'

Manganese. Another noticeable fact was the discovery in these various deep-sea deposits, but most abundant in the red clay, of the peroxide of manganese. It occurs widely distributed in the form of minute grains, concretions, nodules, and flat aggregations and incrustations on and around organic substances[2]. Some of the nodules are of the size of an orange.

Distribution of the shallow and deep-sea Fauna. Mr. Murray says of the 'shore-deposits,'—confirming, in most respects, the early original

[1] 'Voyage of the "Challenger,"' vol. ii. p. 369 *et seq.*
[2] Murray, 'Proc. Roy. Soc.' vol. xxiv. p. 529.

work of Ehrenberg in other and more limited areas,—that in the green muds, at a depth of from 50 to 700 fathoms, beautiful casts of Foraminifera, with shells of Pteropods, Echinoderm-spines, and other calcareous organisms, occur in great numbers. River-muds, in which Pteropods, Radiolaria, and pelagic Foraminifera are usually wanting, are included in these 'shore-deposits.' Then down to a depth of 1500 fathoms the shore-deposit was generally found to contain Pteropod, larval Gasteropod, and Lamellibranch shells in tolerable abundance, with many of the shore-forms of Foraminifera, as Lagenæ, Nodosariæ, Uvigerinæ, Textulariæ, Rotaliæ, etc. Pelagic Foraminifera also occur, but not in such abundance as in the true (abyssal) ocean-deposits. The frustules of Diatoms and their broken parts are numerous. Pieces of wood, fruits, portions of fruits, and leaves of trees are also found imbedded in these muds.

Beyond 1500 or 1700 fathoms Pteropod and Heteropod shells are usually not found, and in 3000 fathoms hardly a Foraminiferal or calcareous organism remains, only Radiolaria and Diatoms, though these siliceous organisms occur locally at all depths.

The *Globigerina ooze* consists largely of the calcareous shells of this small Foraminifer; but with them are in places many remains of the siliceous shells of Radiolaria and Challengeriæ, and Diatoms. In certain limited areas (*Radiolarian ooze*) the siliceous exuviæ of Radiolaria, and in others Diatoms, prevail, with only the occasional occurrence of a Globigerina.

Sponges. In their geological relations the forms and distribution of the Sponges are of the highest interest. Sir Wyville Thomson says that they are found at all depths, but in greatest numbers between 500 and 1000 fathoms; that Calcarea seem to be confined to shallow water; and that at great depths Hexactinellidæ preponderate. Those forms, which occur in the fossil state in the earlier Palæozoic rocks, and are represented by the Ventriculidæ and allied families in Cretaceous strata, show the wide extension in space of a very uniform deep-sea sponge-fauna. Among these genera are Holtenia, Hyalonema, Euplectella, etc., which have beautiful siliceous skeletons. Nearly all the deep-sea sponges are stalked, or provided with fringes of radiating spicules, to support them above the surface of the soft ooze on which they grow.

Corals were found to have a wide range of depth. Professor Moseley gives a list of forty-two genera found by the various English, American, and other expeditions in depths from 50 to 1500 fathoms; one genus (Bathyachis) having even been found to range from 30 to 2750 fathoms. Of these genera twenty are known to occur also in a fossil state. Two make their first appearance in the Liassic, six in the Cretaceous, and the remainder in the Tertiary period. As the bathymetrical distribution of these genera is of much geological interest, I annex a Table

of their range in depth and in time, compiled from the lists in Professor Moseley's[1] preliminary report.

		Range of depth in fathoms: above	between				below
		250 fms.	250–500	500–750	750–1000	1000–1500	1500 fms.
	Turbinolidæ.						
Tertiary Genera.	Acanthocyathus	—	—				
	Deltocyathus	—	—	—	—	—	
	Sphenotrochus	—					
	Platytrochus	—					
	Ceratotrochus	—	—	—	—	—	
	Desmophyllum	—	—	—	—	—	
	Flabellum	—	—	—	—	—	—
	Oculinidæ.						
	Oculina	—					
	Lophohelia	—	—	—			
	Balanophyllia	—	—				
	Dendrophyllia	—					
	Amphihelia	—	—	—	—	—	
	Turbinolidæ.						
Cretaceous Genera.	Caryophyllia	—	—	—	—		—
	Cœnocyathus	—					
	Astræidæ.						
	Parasmilia	—	—	—	—	—	
	Cœlosmilia	—					
	Eupsamidæ.						
	Stephanophyllia	—					
	Turbinolidæ.						
Liassic Genera.	Theocyathus	—	—				
	Trochocyathus	—	—				

Amongst the new forms found by the American Coast Survey, and described by Count Pourtales, there are two genera (Haplophyllia and Guynia) which were thought to belong to the Palæozoic group of the Rugosa.

Mopsea, a London-clay genus of Alcyonaria, is very abundant in some seas in comparatively shallow water down to depths of 1000 fathoms.

Echinoderms. Of the other classes of Invertebrata Sir Wyville Thomson remarks[2] that, amongst the Echinodermata, forms belonging to Pentacrinidæ occur in depths of from 300 to 500 fathoms. Apiocrinidæ, of the pedunculate genera Rhizocrinus, Bathycrinus, and Hyocrinus, are occasionally found at greater depths. Ophiuridæ were found at the greatest depths. Asteridæ abound at moderate depths; and the aberrant Brisinga was found everywhere at depths of from 400 to 3000 fathoms. Sea-urchins of the genus Procidaris, and the Cretaceous genus Salenia, occur not unfrequently; while a number of genera closely allied to Micraster and Ananchytes of the Cretaceous seas were found abundantly at depths of from 1000 to 2000 fathoms.

The various orders of Crustacea form an important group in the ocean fauna. Cirripedia, some of them large and highly ornamented, were found at the greatest depths. Macrurous Decapods, including

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[1] 'Proc. Roy. Soc.,' vol. xxiv. p. 565.

[2] 'Voyage of the "Challenger,"' vol. ii. pp. 328–356.

some large shrimps, likewise occurred at great depths; but brachyurous Decapods appeared to be confined almost entirely to comparatively shallow water.

Annelids were not abundant at great depths, though in one place they seemed to be almost the sole inhabitants of the abyssmal red clay.

Molluscs, etc. Polyzoa were found at all depths.

Brachiopoda were found widely distributed, but by no means numerous, either in species or individuals.

The great groups of the Lamellibranchiata and the Gasteropoda do not enter largely into the fauna of the deep sea, and they are usually small and stunted. A fine *Volute* was, however, dredged in 1600 fathoms in the Southern Seas; some fine species of *Margarita* in 1260 and 1675 fathoms; and a large bivalve allied to *Lima* in deep dredgings at widely separated stations in the Atlantic and Pacific.

The shells of Pteropods and Heteropods make up a large portion of some beds deposited on banks where there is relatively little land débris. They continue to abound in depths of less than 1500 fathoms; deeper than this they become more and more rare[1]. These shells, like many of those of Globigerina, are derived from inhabitants of the surface-waters, where species of these orders sometimes swarm in the open ocean.

Cephalopoda were only brought up occasionally, and not from any great depth.

Fishes. According to Dr. Günther[2] the fish-fauna of the deep sea is composed chiefly of forms, or modifications of forms, which are found represented at the surface in the cold and temperate zones, or which appear as nocturnal pelagic forms. The Chondropterygians are but scantily represented, and are confined to depths not exceeding 500 to 550 fathoms. The Acanthopterygians range from 200 to 2400 fathoms; Acanthini are very numerous; Gadidæ, Ophidiidæ, and Macruridæ range through all depths and constitute about one fourth of the whole deep-sea fish-fauna. The Scopeloids constitute nearly another fourth.

The greatest depth, which can be accepted as one at which Fishes undoubtedly live, is 2750 fathoms,—a depth at which *Bathyophis ferox* was dredged.

The colour of deep-sea fishes is generally black or silvery. The eyes in most species increase in size, down to 200 fathoms, beyond which depth there are small-eyed and large-eyed fishes. In the greatest depths blind fishes occur with rudimentary eyes and without special organs of touch. Many fishes of the deep sea are provided with more or less numerous small, round, shining, mother-of-pearl coloured bodies imbedded under the skin.

[1] Murray, *op. cit.* p. 536.

[2] 'The Study of Fishes,' pp. 296–311.

A point of extreme interest to the geologist is the occurrence, in the Red Clay, at great depths and far from shore, of Sharks' teeth of all sizes (one was four inches across the base), and of the tympanic ear-bones of Cetaceans, often in great numbers. In some instances the trawl-bag brought up over a hundred sharks' teeth, and between thirty and forty ear-bones. These are frequently imbedded in a deposit of manganese, or have served as nuclei for nodules of the manganese to form on. These fish remains are considered to belong to some late geological period.

One important conclusion arrived at is that there is not a general distribution of life over the great ocean-beds; for, although life exists at all depths, there are large tracts in the various zones which were found to be barren, and where for days together the dredge came up empty.

Absence of Extinct Genera. It results from these investigations that the population of the *open oceans* may be divided into two classes—the one inhabiting the deep ocean-bed, the other living in the surface-waters only; while the intermediate depths of water are void of life. Another important fact comes out. Although we are introduced to many new and curious genera and species, and to forms very analogous to those of some geological periods, no identity of species[1] has been established with those periods, and no extinct genus has been recovered. Nor can it even be said that the analogous forms are more than might be expected from analogy of certain physical conditions, and show any greater or closer relationship than do these forms with which we were already acquainted in the shallower waters before explored. The only identity with the geological fauna (except in the case of such low forms as Foraminifera, etc.) has been the discovery of a few species of Pliocene Mollusca which were not hitherto known to be living; but similar discoveries had been before made from time to time in the shallower seas.

It must be remembered, however, that the explorations of the deep oceans, although extending over wide areas, form but the finest of lines across comparatively unlimited plains. Much has been done, but infinitely more yet remains to be done; and we know not what future researches may bring to light. Still, from analogy, we may expect the extension of the already discovered new populations rather than the discovery of one altogether aberrant from those already known of the present period.

Professor T. Fuchs[2] has made a curious suggestion, that it is light, and not temperature, which regulates the distribution of the littoral and ocean faunas. He thinks that the depth of 300 feet may be regarded as the boundary of the former, or *the fauna of light*, and that beyond is a comparatively sterile region with only a few stragglers from above and

[1] Except in Foraminifera.
[2] 'Mag. Nat. Hist.' for Jan., 1883.

below, and extending down to about 500 feet; while all below that depth are the deep-sea fauna, or *the fauna of darkness*.

The Norwegian Seas. The observations of the Norweigan naturalists[1] in the basin of the Northern Atlantic between Norway and Greenland have shown that the conditions which there prevail are very similar to those observed by the 'Challenger' in other parts of that ocean; the differences being only such as are dependent on local conditions. The depth of this part of the Atlantic varies generally from about 6000 to 9000 feet, attaining in the centre of the basin 12,000 feet, and the fall being very rapid along the coast of Norway. Along the whole of that coast a grey clay, very slightly calcareous, extends to some distance from land, and to depths of from 4000 to 6000 feet. It contains the remains of a littoral fauna, and the characteristic Foraminifer is a species of *Uvigerina*; it is separated from the next named deposit by a zone of brown transitional or passage clay.

In the deeper central part of the basin a lighter coloured and very calcareous clay, to which they have given the name of *Biloculina clay*, from the abundance of this Foraminiferal species, extends from depths of 4000 or 5000 feet to the greatest depths reached. Mixed with these are a few *Globigerinæ*, but Foraminifera are not so abundant as in the Mid-Atlantic ooze. In the shallower waters between Spitzbergen, Norway, and Nova-Zembla, a green clay with *Rhabdammina* spreads over the sea-bed.

In most parts of this sea small pebbles of crystalline and volcanic rocks, sandstones, etc., are common. One point of especial interest noted was that fragments of flint and chalk occur over the whole of the area, even as far north as lat. 78°. Among them was one Chalk *Belemnite*.

Ocean Depths and Currents. Notwithstanding the inequalities of the land and the altitude of mountain-ranges, the mean height of the continents above the level of the sea is very far from equalling the depth of the depression below the sea. Humboldt estimated the mean height of the land to be 671 feet in Europe, 1062 feet in Asia, 702 feet in North America, and 1080 feet in South America, above the level of the ocean[2]. The greater portion of these continental areas is of very moderate height, and the mountain-chains are only long, narrow, elevated ridges a few miles in width. The ocean depths, on the contrary, form, not inverted ridges, but vast depressions of great extent both longitudinally and transversely. The valleys of the ocean present little resemblance to those of the land: they are deep basins or broad troughs, generally of much uniformity, and extending without interruption for hundreds or even thousands of miles. In the Atlantic ocean there are two long troughs from 12,000 to 20,000

[1] The Norwegian North-Atlantic Expedition, 1876–8.

[2] See letter of Mr. J. Carrick Moore to 'Nature,' April 18, 1872. Other calculations have been made, but they do not seem to me so probable.

feet deep, between which rises an irregular ridge only about 6000 feet below the surface. In the Eastern Pacific a more uniform depth of 10,000 to 12,000 feet prevails, while in the Western North-Pacific the depths become greater, the deepest sounding of 27,450 feet having been made in lat. 11° 24′ N., and long. 143° 16′ E. (For some of the contour lines of depth see Map, No. II.)

In high northern latitudes the Atlantic becomes less deep. In the sea north of Britain the depths attained reach from 6000 to 12,000 feet, and in the Spitzbergen seas they diminish to 5000 and 6000 feet. On the other hand, along the ice-barrier in the Antarctic seas the depth seems to be not less than 12,000 feet.

It has been variously estimated that the average depth of the Atlantic is from 13,000 to 15,000 feet, whilst that of the more northern Atlantic probably does not exceed 8000 feet. The average depth of the Pacific may be somewhat greater than that of the Atlantic. If, therefore, we were to take the mean height of all lands at 900 feet, and the mean depth of the ocean at 13,000 feet, and the area of the former with regard to the latter to be as 1 : 2·8, then it would appear that the mass of the land above the sea-level is to the volume of water in the proportion of not more than about 1 : 42. But these at present can only be roughly approximate estimates.

Distant from land and inaccessible as the deeper of the great ocean troughs are, there is reason to believe that currents sweep over their whole breadths and reach down to the greatest depths; for everywhere is the composition of the ocean waters alike, and everywhere a similar order in the distribution of temperature at depths prevails. Consequently, the finer débris of the land carried incessantly down into the seas by all the rivers of the world is, where the action of the river waters cease, caught up by these great marine currents and swept to places far beyond the more apparent tidal action. It is only when the seas are enclosed, or when the ocean currents are weak, that the check to this river action leads to the earlier precipitation of the transported materials and to the more ready formation of deltas. The fine sediment, as shown by the 'Challenger' observations, is carried to very considerable distances from land, and it is a question whether some of the amorphous matter of the abyssal oozes, apart from the decay of the volcanic débris which seems to have floated on the surface, may not be ordinary sedimentary matter transported from a distance.

The geological interest of these great currents consists not only in the transport of sediment, seeds, and plants to great distances, but also in their influence on land climates. A certain number of these currents proceed from the Arctic and Antarctic seas and sweep down towards the Equator; others again proceed from the Equator and run towards the polar regions.

This is not the place to describe these currents in detail[1]. On the map (No. III.) are given the position and course of the principal ocean currents, the influence of which is shown in the excessive deflection of the summer and winter isothermal lines laid down on the same map. Thus, while the cold currents sweeping down from the Greenland seas carry ice and cold winds down the east coast of North America to lat. 40° N., the Gulf Stream and equatorial current carry northward their warm waters, and deflect the winter isotherm of 32° from that same southern latitude to the high northern latitude of 70° in the sea between Iceland and the North Cape. The limits of the drift-ice, which in the Arctic Atlantic lies between Spitzbergen and Nova Zembla in lat. 75° N., reaches to lat. about 70°, or 300 to 400 miles further south, in the seas north of Behrings' Strait, because of those narrow and shallow straits staying the passage to the northward of the warm south currents of the Pacific. An analogous condition of things would exist in these latitudes if a belt of land between Britain and Greenland intercepted the warm streams from the more southern Atlantic, in which case we might possibly see the mountains of the Scandinavian Peninsula again covered, like Greenland in nearly parallel latitudes, with a permanent sheet of ice and snow.

The width, depth, and velocity of the great currents vary considerably. The warm waters of the Gulf Stream off the coast of America are not more than 600 to 1000 feet deep, and though the stream becomes wider as it flows northward, while its depth diminishes to less than 100 feet, it still helps, with other currents, to carry the warm southern waters to the coasts of Norway and Spitzbergen. On the other hand, the great Humboldt Current passes up the west coast of South America,—a majestic body of polar water not less than 6000 feet deep with a velocity equal throughout[2],—and so tempers the surface-waters even at the Equator, that, instead of the normal temperature of 80° to 84° F., they are even within the tropics often not higher than 58° to 60° F.

The Gulf Stream on the coast of Florida has a velocity of from 60 to 100 miles per day. This gradually decreases to twenty-four miles off Newfoundland and to five miles between the British Isles and Iceland. This may be taken to represent the ordinary velocity of ocean currents, though sometimes they far exceed this. Professor Moseley remarks[3] that he never realised the strength of an oceanic current until he saw in mid-ocean the equatorial current rushing past St. Paul's Rocks with the velocity of a mill-race,—a current which at times baffles a ship's boat in its attempts to pull against the stream.

[1] For full information on this subject the reader should consult the several papers on the influence of the Gulf Stream and other currents by Dr. Carpenter and Dr. Croll.

[2] 'Voyage de la Vénus,' vol. v. p. 144.

[3] 'Notes of a Naturalist on the "Challenger,"' p. 68.

Temperature at Depths. Not less important than the action of the surface-currents in bringing the warm equatorial waters to lessen the severity of more northern climates and the cold waters of the Arctic and Antarctic seas to temper the heat of the equatorial regions, are the deep-seated slow-creeping currents which proceed from the Polar seas and pass at great depths to or beyond the Equator. In the Atlantic the Antarctic waters seem to surge up as they approach the Equator, but in the Pacific they pass further north. While the warm surface-waters of the equatorial regions have a special littoral fauna localised by a high temperature, the littoral- and shallow-sea inhabitants of the cold and temperate waters of the northern seas are, by means of these deep and wide-spread currents, able to migrate southward and live in the cold depths of the ocean waters, for it would seem that for their survival temperature is of more influence than depth or light. Consequently, the geologist has to be careful not to infer, without other evidence, from the presence of northern species or genera, that the land climate was necessarily a cold one; on the other hand, he may more safely infer, from the presence of tropical forms, that the climate of the period or place was a warm one.

The general fact of the presence of cold waters at depths of the ocean, and of the transfer of the polar and equatorial waters, had been previously known, but it was not until the voyage of the 'Challenger' that the deep isotherms of the great oceans became systematised. For the temperature of the Arctic seas we are still dependent upon the observations of our earlier Arctic voyages, and of some of the great French expeditions. They furnish us with the submarine temperatures of the Spitzbergen seas [1], Baffin's Bay, and other less frequented seas. From these we learn that while in the great oceans there is a uniform temperature at depths of from 35° and down to, but nowhere descending below, 32°, the temperature of the Arctic open seas may be warmer beneath than at the surface, although at depths and near the land the temperature of the water seems to range down to as low as 28°; but further observations are wanted on this point.

No such uniformity of increasing cold with increasing depth obtains in enclosed or partly enclosed seas. In these latter the temperature at depths is regulated, not by submarine currents, but by the mean annual temperature of the region. Thus, in the Mediterranean the temperature at depths (7000–8000 feet) is about 55° F., whereas in the Red Sea (3000–4000 feet) it is as high as 70·5° F.; while in the more northern seas, such as the Sea of Okhotsk, the temperature at depths (690 feet) is only 28·6° F., and in Baffin's Bay and Davis Strait, Sabine and Ross record temperatures of

[1] See the voyages of Scoresby and of 'La Recherche.' These, together with the Mediterranean observations of Aimé and others, will be found described in my paper 'On Submarine Temperatures' in the Phil. Trans. for 1874, vol. clxv. p. 587.

28·7° and even of 27°. These last temperatures may appear abnormally low, but the reader will bear in mind that, although the temperature of greatest density of fresh-water is 39·2°F., that of sea-water (of 1·027 specific gravity) is as low as 25·4°, and its point of congelation 27·4°; and that these points vary with the salinity of the water.

In any case, the temperature in all the open oceans decreases rapidly with the depth, and the layer of surface warm water is very superficial. This is shown generally in the following temperature-sections in the Atlantic, from the Equator to near Spitzbergen: the first three are from the 'Porcupine' and 'Challenger' expeditions.

ATLANTIC SECTIONS.

Depth in feet.	3½ degrees South of the Equator.	23 degrees North of the Equator.	55 degrees North of the Equator.	78 degrees North of the Equator.
0	78°	73·4°	57·2°	32°
120	-	-	53·5	-
270	68	-	-	-
300	—	-	50	—
310	-	-	-	33·5
360	59	-	-	-
420	-	70	-	-
780	-	64·5	-	-
960	50	-	-	-
1140	-	59	-	-
1440	-	55·4	-	-
1500	-	-	48·2	-
1800	-	51·8	-	-
1920	41	-	-	-
2040	-	50	-	-
2280	-	48·2	-	-
2460	39·2	-	-	-
2640	-	46·4	-	-
3000	—	47·6	—	—
3300	-	-	46·4	-
3600	-	42·8	-	-
3900	-	-	44·6	-
4200	-	-	42·8	-
4566	-	-	-	35·5
4650	-	-	41	-
5400	-	39·2	39·2	-
6600	37·4	-	-	-
7200	-	37·4	-	-
8400	-	-	37·4	-
9000	36·5	—	-	-
11,760	-	35·5	-	-
12,000	33·7	—	-	-
13,200	33	-	-	-
15,760	-	35·3	-	-

Another effect, resulting from these low submarine temperatures combined with the action of currents, for the geologist to consider, is the lowering of the temperature which they cause on the coasts, and around some oceanic islands on which they impinge. If the cold lower layers

of water meet with a shoal, they are deflected, and are carried over it; and in the same way a shelving coast-line deflects them upwards on the shore in the manner shown by the following diagram. The bearing of these various phenomena upon the distribution not only of marine life, but also of the land fauna and flora, and upon the condition of inland or partially enclosed seas, will be more apparent to the student when he comes to questions of palæontological and stratigraphical geology.

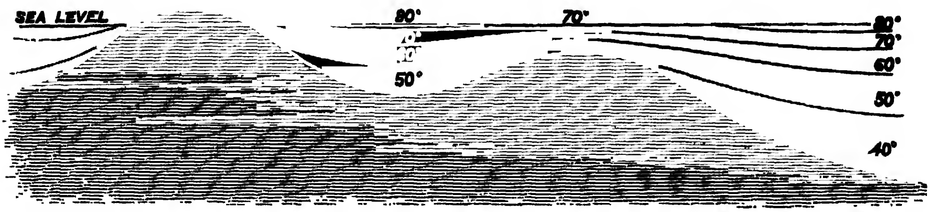

FIG. 41. *Diagram to show the rise of the Isothermal Lines of Depth over a Shoal or against a Coast.*

This presence of cooler waters over shoals is a fact long known to navigators.

NOTE.—Since these pages were in type, two volumes of valuable 'Reports on the Scientific Results of the Challenger Expedition,' by Commander Tizard, Professor Moseley, Mr. J. Y. Buchanan, and Mr. John Murray, have appeared (March 1885). As the abstracts given in this chapter are based upon the Preliminary Reports only, there may be some discrepancies requiring reference to these complete Reports, which the student in any case would do well to consult.

CHAPTER IX.

METEOROLOGICAL AGENCIES.

THE VARIOUS AGENTS. THE SURFACE-SOIL. ITS PROTECTIVE CHARACTER. PERMANENCY OF OLD EARTH-WORKS. AGE OF TREES. WORM-ACTION ON SOIL. SOLAR HEAT. TEMPERATURE OF SURFACE. NO VARIATION WITHIN HISTORICAL TIMES. DIRECT EFFECT OF THE SUN'S RAYS. EXPANSION OF ROCKS. ACTION OF FROST. ROCKS AND ICE CONTRACTED BY COLD. DR. RAE'S OBSERVATIONS. INFLUENCE OF AIR AND MOISTURE ON ROCKS. CHANGES AND LOSS OF COLOUR. GREEN SANDS AND IRON SANDS. ALTERATION OF CLAYS. WEATHERING OF OCHREOUS GRAVELS AND CARBONACEOUS SANDS. SOLVENT ACTION OF SURFACE WATERS ON CALCAREOUS STRATA. ACTION OF THE WINDS. TRANSPORT OF SAND, ASHES, SEEDS. FORMATION OF DUNES. EFFECTS OF STORMS. FLOODS. FULGERITES. ROCKS STRUCK BY LIGHTNING. METEORITES: THEIR NUMBER AND SIZE. MONUMENTAL FORMS OF WEATHERED ROCKS.

Atmospheric Agencies. Amongst the most important of these agencies in respect to their action on the various rocks are heat and cold, frost, air, moisture, winds, and storms. Without these the globe would present a succession of rock-surfaces coextensive with the superficial area occupied by each geological Formation. The strata which crop out to the surface would each retain their original petrological characters; and the aspect of the earth would be like that presented by a geological map. But by the incessant operation of the various meteorological agencies the surface of the land is weathered and disintegrated, and has become covered with a coating of soil, resulting from the decomposition of that surface and of the plants which have grown upon it. This coating, while it has obliterated the substructural features, serves the great purpose of rendering the earth fertile and subservient to the uses of man.

Surface-Soil. The soil, which results from the decomposition of the surface, partakes to a certain extent of the character of the rocks beneath, greatly modified, however, by the action of rain and animal life which have intermingled the component parts of the soil and helped to give it a uniform character; and this has been further increased by the growth and decay of vegetation, which has supplied a common colouring matter; while the action of the rain, through long ages, has had the effect of dissolving and removing the carbonate of lime from the soil, notwithstanding that it may be abundantly present in the rocks below. Thus, in

some Oolitic and Limestone districts a soil almost perfectly free from lime often covers the surface of the calcareous rocks.

This surface-soil, with its usual covering of herbage, serves to protect the land from further degradation, and checks the denuding action which would otherwise scour the surface after every shower of rain. Instances have been adduced to show how persistent are the features of such a surface. The position of the many dolmens and other so-called 'Druidical' stones, so common on the downs of this country and in many parts of France, shows that the level of the vegetable soil has undergone little or no change since they were first erected. The camp of Attila, situated in the great chalk plains of Champagne, furnishes a well-known date, namely A.D. 451. Notwithstanding its more than 1400 years the surface of this great earthwork, which is merely covered with a thin growth of grass, remains almost as perfect and as sharp as when first made and grassed over. Nothing of importance has been removed from the surface by mechanical means, whatever may have been the solvent action of the rain on the rocks beneath.

The many old British and Roman camps in our own country, such for example as the large and well-preserved one known as Maiden Castle near Dorchester, attest to the same general fact. But although there is little disturbance of the soil, there has been evidently a removal of the carbonate of lime from the body of these chalk mounds; for it has been redeposited in places among the rubble at their base, cementing it into a compact chalk-breccia.

In further proof of the permanence of the surface-soil in many localities may be instanced the age of some of the large trees growing in several parts of the world. In the forest of Fontainebleau there is an oak which is said to have sheltered Clovis. In the Ardennes there was another, the age of which was ascertained to be not less than 1500 years. In England some of the yew trees on our chalk downs are supposed to have attained the age of 2000 years. Finally, there is the remarkable case of the boab trees in the Cape-Verde Islands and in Senegal, some of which may, it is supposed, be from 5000 and 6000 years old.

Under certain conditions it is true that stones and even blocks of considerable size may, as Darwin has shown, disappear and become buried beneath the surface-soil by the action of worms. Their castings, incessantly brought up by them to the surface, suffice in the course even of a generation or two to level and make smooth stony fields, though, geologically, this is merely a transfer of the finer particles to the surface and the lowering of the coarser materials below the surface. I would refer to the many curious instances recorded in Darwin's recent work [1].

Solar Heat. There are two sources of heat on the surface of the

[1] 'On the Earthworm.'

earth, namely, that which is radiated from the sun, and that which is received by conductivity from the interior of the globe. At the present time the secular refrigeration has proceeded so far that there is very little loss of heat from the interior by radiation into space, and therefore the heat of the surface depends essentially upon that which the earth receives from the sun. This source of heat is one the effects of which are subject to great variations, according to the length of the day, and the angle at which the solar rays impinge on the surface.

It has been found that the mean temperature of the soil at a depth of 3 feet at Stockholm is 43½° F., while at Trivandrum, in Southern India, the mean temperature of the soil has been found to be 79½° F., and at Rio Janeiro 76° F. On the other hand, observations made in sinking a well at Yakoutsk, in Siberia, gave a temperature of 6° F. at a depth of 7 feet.

In general the diurnal inequalities are insensible beyond a depth of 3 feet, while the annual inequalities extend in these latitudes to an average depth of 50 to 60 feet. The temperature at this depth is that of the mean annual temperature of the place. Forbes's observations showed, however, that in the neighbourhood of Edinburgh the depth at which the annual range of surface temperature is reduced to 0·01° C. in various rocks is from 57·3 feet to 98·9 feet,—being that at which the climatal changes cease to be operative. The line of permanent temperature varies therefore considerably with the nature of the strata. In the cellars of the Observatory in Paris, at a depth of 28 mètres (92 feet), the thermometer registers 11·7° C. (53° F.) invariably. The mean annual temperature of the air at Paris is 10·6° C. (51·1° F.). At Greenwich it is 49·5° F.

Pouillet endeavoured to determine the quantity of heat that the earth and atmosphere receive annually from the sun. He found that, when the atmosphere is perfectly serene, it absorbs nearly half the quantity of heat which the sun radiates to the earth, and that it is only the other half of this quantity which reaches the surface of the earth; and he concluded that if the quantity of heat which the earth receives from the sun in the course of the year were uniformly distributed to all points of the globe, and could be all employed in the melting of ice, it would be capable of melting a stratum of ice 102 feet thick, covering the whole earth [1]. Were it therefore possible that any cause should affect the amount of heat given off by the sun, it is conceivable, with the low temperature prevailing in space, variously estimated at from 60° F. to 120° F., that the general temperature of the earth might at times be reduced, or that it might be subject to a certain amount of variation.

The effects of solar heat on the globe do not however appear to have varied within the historical period. Arago has shown that 'the mean temperature of Palestine has not undergone any sensible change since

[1] 'Éléments de Physique,' 5th edition, vol. ii. p. 682.

the time of Moses,' or for more than 3000 years. He points out that for the vine to be cultivated with success, and at the same time for the date to ripen, as is the case in Palestine, the hot-weather temperature must not be less than 70° F., which is in effect the mean summer and autumn temperature of Jerusalem. The climate of Rome and the south of France is also sensibly the same as it was in early historical times; for it is well proved that the range of cultivation of the vine and of the olive still has the same limits as in the time of the Romans.

The direct effect of the sun's heat has in temperate climates little influence on the surface-rocks; but in tropical climates it is a far more active agent, drying up and rendering desert large tracts of land, and promoting both chemical and mechanical action. Rocks slightly expand and contract according to variations of temperature; and the alternate expansion and contraction tend to disintegrate and loosen their surface. Dr. Livingstone 'mentions that in Africa he found the rocks which during the day were heated up to 137° F., had their surfaces so rapidly cooled by radiation at night, that the contraction was sufficient to split the stone, and to throw off sharp angular fragments from a few ounces to 100 or 200 lbs. in weight.'

The rate of expansion in rocks varies considerably, as will be seen by the following results Adie obtained by exposing rock-specimens of a given size to a range of temperature of from 32° F. to

	Decimals of linear expansion for 180° F.	for 1° F.
Galway black marble . . .	·0004452	·00000247
Carrara marble . . .	·0006539	·00000363
Aberdeen granite . . .	·0007894	·00000438
Ratho greenstone . . .	·0008089	·00000499
Penrhyn slate	·0010376	·00000576
Craigleith sandstone . . .	·0011743	·00000652

Action of Cold on the Surface. The change of volume which takes place with variation of temperature affects in a very powerful way the surface of the land in northern latitudes. All travellers have described the excessive waste and wear caused by the winter cold in arctic regions. This is often attributed to the absorption of moisture and its subsequent freezing and expansion. But the change of volume from mere changes of temperature is probably a more general agent. Captain Beechey, speaking of Spitzbergen, says that, in consequence of the intense cold, masses of rock are repeatedly detached from the hills, accompanied by a loud report, and, falling from a great height, are shattered to fragments at the base of the mountain, there to undergo a more active disintegration. Similar observations were made by Dr. Kane in North Greenland, where the waste of the cliffs by frost goes on every year on a great scale. Sir R. Maclure states that some of the islands in Barrow's Straits, which consist of strata

of hard limestone, have their surface, owing to the intense cold, broken up and covered with a mass of fine angular shingle. In other cases sandstones are disintegrated and converted into loose sands.

It is not necessary to multiply these examples. Everywhere in Arctic regions the hardest rocks are rent, enormous blocks displaced and thrown down, and vast taluses of angular fragments fringe all the heights; and the same action, though less energetic, goes on in the mountain-chains of more temperate climates. That it is not altogether due to the expansion of water in porous and fissured strata is shown by the circumstance that it is not confined to the first frosts, and it equally affects ordinary as well as crystalline rocks and compact limestones, which absorb little or no water, and appears to be as frequent in the depth of winter, when all is under snow and ice, as at the insetting of the winter. Under the action of these joint influences the disintegration of the surface in Arctic regions is excessive.

These changes of temperature alter not only rocks, but their action on ice is equally marked. It has been found[1] that, under the influence of cold, ice follows the same law as other bodies, and contracts; and that the contraction is even greater than that of any other solid bodies. Thus, between zero of Centigrade and $-20°$ C. ($+32°$ to $-4°$ F.) ice increases in density as under:—

Ice at $1°$ C.	has a	density of	0·91800
„ $-5°$	„	„	0·91856
„ $-10°$	„	„	0·91912
„ $-20°$	„	„	0·92025

This gives a linear contraction equal to 0.0000375 for each degree Centigrade, or ten times greater than that of Carrara marble.

Dr. Rae[2] informs me that, in encamping for the night, in winter, on the shores of a large frozen lake, such as Lake Winnipeg, should the temperature fall rather suddenly 10°, 15°, or 20° (no unusual circumstance), loud cracks, like pistol-shots, are heard on the lake. When the party resume their journey over the lake in the morning, they usually come to cracks in the ice, sometimes two or more feet wide, in fact, sometimes so wide that it is difficult to jump over them. Should the cold continue for a day or two, these cracks rapidly freeze up. When the temperature rises the ice expands, and as the volume of ice is now too large for the lake by the amount of new ice formed in the cracks, ridges of ice are pushed up at certain places, and on the shore. When another cold "snap" comes on, these ridges as a rule do not settle down, so fresh cracks are formed; and this process of contraction and expansion goes on for a considerable part of the winter. Even the smallest lakes show this action in

[1] Brunner, 'Ann. Chem. and Phys.,' vol. xiv. p. 369.
[2] Letter to Author; and Richardson's 'Expedition to the Polar Sea.'

a greater or less degree, according to their size, whenever a sudden change of temperature takes place. As a result of this, in many lakelets having stony shores the stones are ridged and packed together in a manner and with a regularity that resembles the work of man.

When the ice is 3 or 4 feet or more thick, the cracks appear as before on sudden cold, but they are not so wide, and are more numerous; they are then also wedge-shaped, and often do not extend to the water, owing to the extreme cold contracting the surface and upper portion of the ice, whilst the warmer water keeps up the expansion of the under surface. Of course, the greater the cold, the more deeply does the contracting influence extend.

Dr. Rae mentions as an instance of the movement in ice produced by this cause, an attempt to carry a viaduct across a long shallow lake. Piles were driven in and the road constructed in summer, but in winter it was found that the movements of the ice, caused by alternations of temperature, pushed the piles over, and the road had to be abandoned. This road was nearer to one end of the lake than the other, and at the end where probably the ice was weakest, and where it most readily gave way to pressure. There were no currents nor any other perceptible movement of the ice to account for what took place.

Influence of Air and Moisture on Sedimentary Strata. We have already had occasion to notice the effects produced on rocks of igneous origin by the decomposition of their silicates, caused by the action of the atmosphere combined with moisture. I would now direct attention to some of the alterations which sedimentary strata suffer from the same cause. Although productive of infinitely less actual decomposition, these changes in the sedimentary strata are nevertheless of importance from the differences they often produce in the aspect of the strata, the deceptive appearances to which they give rise, and the extent of the superficial decalcification. Rocks originally grey, or blue, are changed to light yellow, red, or brown. Ochreous and even blackish beds become white, and dark greens pass into browns and reds.

Alteration of Colour. These changes are due to the oxidisation of the metallic bases by air and moisture, and to de-oxidisation by organic matter. Thus some of the grey argillaceous limestones or marls of the Lias, or of the Kimmeridge, and similar argillo-calcareous strata, which imbibe small portions of water, become light-yellow or brown for some distance from the lines of joint and bedding. Sometimes the whole mass is bleached; but more frequently central dark cores are left. This alteration is due to the circumstance, that almost all these argillaceous limestones owe their bluish-grey colour to the presence of a small quantity of bisulphide of iron (iron-pyrites), or of some carbonaceous matter. The former, when exposed to the action of air and moisture, is decomposed and

changed by oxidisation of the sulphur and iron, into the sulphate of the protoxide of iron; and this in its turn is decomposed, the acid uniting with some of the earthy or alkaline bases present, and the protoxide passing into a hydrated peroxide. The rock consequently loses the dark colour due to the original pigment, and retains only the slight tinge due to the presence of the iron-peroxide (see p. 28).

When the colouring is due to organic or carbonaceous matter alone, the alteration is effected merely by the slow oxidisation or *eremacausis* of the organic matter by the air and moisture. The organic colouring matter is thus often completely destroyed, while the resulting carbonic acid is carried off by the permeating waters, either alone or in combination as a carbonate of some substance.

This alteration, owing generally to the greater permeability of the oolitic and other freestones, extends in them to greater depth than in the more compact rocks. In these it has generally removed the colour of the whole mass of the strata above the line of permanent water-saturation; and it is not until a depth considerably below the surface is reached, that the rock is found to retain the grey colour it originally had.

The presence of minerals with a base of iron-protoxide, as glauconite, gives some rocks a deep bright-green colour. On exposure, the silicate of iron is decomposed, the silica being set free, and the iron, taking up a further portion of oxygen and water, is converted into a hydrated peroxide. Consequently the rock loses its green colour, and passes to yellowish brown, or ferruginous. This action is very marked on the surface of the calcareous iron-ore of the marlstone of the Lias; and the brown colour of some of the oolitic iron-ores may, owing to the permeability of the strata and the consequent influence of the surface-waters at depths, be due to a change of this nature. Some of the fossiliferous iron-sandstones of the Lower Tertiary strata of Kent are not improbably decomposed green-sandstones, and possibly some portions of the Red Crag were deposited originally as green glauconiferous sands.

Among other instances of changes of this nature is that which has affected the Diestien beds of Belgium. At Antwerp they consist of dark glauconiferous and very fossiliferous sands at the base of the Crag series. They are there covered and protected from atmospheric influence by newer light-coloured crags and alluvial beds. At a distance inland, the hills of Belgian and French Flanders are capped by sands sometimes light-coloured and at others ferruginous, with beds of hard iron-sandstone, often pebbly, and (with one or two rare exceptions) without the trace of a fossil. It is nevertheless considered that these beds are synchronous, and these cappings of iron-sandstones ('Diestien') representing merely an altered and consolidated condition of the greensands of Antwerp. The Paddlesworth ironstones above Folkestone, and the Lenham beds, which

I believe to be of the same age and origin, have undergone a similar change. The permeation of the aerated surface waters which has effected the alteration of the mineral matter, has at the same time dissolved and removed the shells, leaving only a few rare casts, while the iron in its new form has acted as a cementing ingredient.

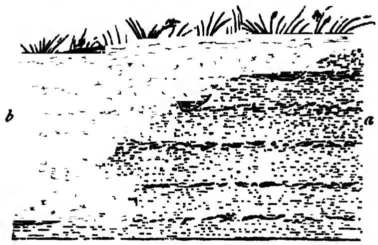

FIG. 42. *Section of Crag on the top of the Cliff at Walton-on-Nase.* *a.* Light-coloured shelly crag. *b.* The same stained by iron-peroxide.

Sometimes, however, the ferruginous colouring of the strata is the effect of staining caused by the subsequent infiltration of iron salts, as Fig. 42.

Argillaceous strata, such as the London clay, Kimmeridge clay, and the Oxford clay, generally contain concretions and shell-casts of iron-pyrites, which, when exposed to the air, decompose and form an efflorescence of the sulphate of iron, which ultimately passes into the brown hydrated oxide. It is to the decomposition of another small portion of iron sulphide dispersed through beds of this class that is due the change which commonly takes place in the London and other of these clays, from dark bluish-grey at depths, to a light burnt-umber-brown near the surface—a change which often extends to some depth.

On the other hand, the influence of vegetable matter in effecting deoxidisation is very marked, as shown in the annexed example taken in the lower part of the cliff near Warden in the Isle of Sheppey. Here the London clay, *a*, is of a dark brown colour, *b* being a piece of wood 2 feet long and ½ foot thick, in the state of lignite. Around this, forming a patch 6

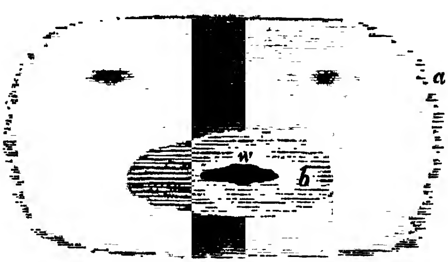

FIG. 43. *In the Clay Cliffs of Sheppey.*

iron was deoxidised and the clay of a light fawn colour.

In marls and clays where magnesia is present, the decomposition of iron-pyrites gives rise to a double decomposition, forming sulphates of lime and magnesia; and to this probably is due the presence of the magnesian salts in the Epsom and Beulah waters. A strong spring of the same kind was met with at the base of the London clay in the New-cross cutting of the Brighton Railway.

Bleached Gravels. A change of another kind takes place in iron-stained superficial gravels, such as are common in the neighbourhood of London, and in the Hampshire Tertiary area. These gravels have a bright ochreous colour, caused by the presence of a small quantity of the peroxide of iron. When they form, as is often the case, moors and commons covered

with heath, or here and there coated with a thin layer of peat, the organic matter carried down by the rain-water reduces the iron-salt from a peroxide to a protoxide, which the free carbonic acid present converts into a carbonate; and this salt, being soluble, is removed by the same surface-waters, leaving the upper part of the gravel colourless, and often quite white. Or it may sometimes be that the humic acid in the soil removes the iron as a soluble humate. The yellow staining of the flints is also removed, and they then present a bleached and white surface. This is of common occurrence in the higher gravels of the Bagshot district, and of the New Forest, where the gravels are heath-covered and old.

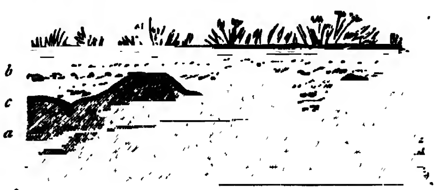

FIG. 44. *Section of Gravel-pit, Bagshot Heath.*—*a.* Ochreous flint gravel. *b.* The same bleached white. *c.* Black layer.

Sands underlying beds of peat are often completely bleached by these processes. It is a feature of common occurrence in alluvial deposits.

A number of analogous examples of similar changes in Cambrian, Permian, Keuper, Jurassic, and Tertiary strata, are given by Mr. Maw in his paper before referred to [1].

Weathering of Limestone. The action of the weather produces another result on calcareous rocks. The exposed surface of these strata is acted upon by the carbonic acid of the surface-waters; and, while the calcareous portion is removed in solution, the insoluble matter in the rock remains behind. As these rocks are rarely pure carbonate of lime,—generally containing more or less sand and clay,—these insoluble portions gradually accumulate on the spot, and form a coating 1 to 2 feet, or more, thick of non-calcareous matter, usually coloured some shade of red or brown by the presence of iron-oxides.

FIG. 45. *Quarry at Imbidie near Cambo.*—*a.* Dark argillaceous limestone. *b.* Brown loam with angular unaltered blocks of the limestone *a.*

Some limestones are more subject than others to this alteration. In

[1] M. Van der Broeck has also given a number of illustrative instances of similar changes in the Quaternary and Tertiary strata of Belgium. See 'Mém. Acad. Roy. Soc. Bruxelles,' vol. xliv. 1880.

this country the residue of insoluble matter rarely exceeds a few feet in depth, but its effects elsewhere sometimes extend to much greater depths. Near Cambo (Basses-Pyrenées) an impure black Jurassic limestone is altered in this way to the depth in places of from 30 to 35 feet (Fig. 45).

In some limestone and oolitic districts the surface-soil may in places be attributed altogether to such weathering. I would not, however, attribute to this origin (as some geologists would do) the widespread bed of red clay with flints overlying so many of our chalk hills. For this clay contains not only numerous sharply angular chalk flints, but also in places flint pebbles and sandstone blocks derived from Tertiary strata. It is also to be observed, that such a soil is much more apt to form over hard impure limestones, on which the water must lodge, with time for it to act, than on permeable pure chalk strata, through which it passes as it falls. When the surface of a hard limestone or oolite is broken and fissured, the fragments are gradually rounded in consequence of the removal of their angles by the acidified waters. In some calcareous gravels, where the surface-waters have followed a definite channel, they have at last entirely removed *all the calcareous fragments*, leaving only that portion of the original gravel which consisted of siliceous sand and *insoluble pebbles*, as shown in the following section, Fig. 46.

In this section *b* represents loam and surface-soil, and *a* a bed of gravel composed almost entirely of small worn fragments of oolitic rocks, with a scant admixture of larger rounded pebbles of quartzite and other old rocks, resting on a base of permeable Oolite; *b′* represents old drainage channels for the surface-water which has worn its way through *b*,—dissolving in its course all the calcareous fragments, and leaving only the insoluble pebbles; the seams of these in *a* being still traceable through *b′*. In another section at Wolvercote hill near Oxford, where the gravel rests on clay and the quartzite pebbles are more numerous, all the oolitic débris has been removed on one side of the section, leaving a gravel of quartzite pebbles only; whereas on the other side the lower part of the gravel retains its original base of oolitic débris. The difference is so great that, if the intermediate portion of the section were not exposed, no one would suppose the two gravels were originally identical; and they would, without the connecting links, be justified in that supposition.

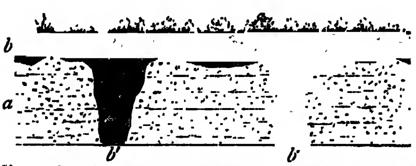

FIG. 46. *Section of a high-level Gravel at Handborough near Oxford.*—*a.* Light-coloured oolite gravel with quartzite pebbles. *b.* Brown loam with quartzite pebbles only.

Few instances of the solvent power of the surface-waters are more striking than the one so common on the chalk hills of this country and the north of France. When the chalk is overlaid by porous sands, or by gravel, or loam, the surface-waters have sometimes removed the upper beds of

chalk, and at other times, when they have found a weak point, they have passed down through the chalk, and in so doing have dissolved away the chalk in funnel- or chimney-shaped cavities, often of considerable depth, and from 5 to 20 feet or more in diameter at top. Cases occur where they extend to depths of 50, 80 and even 100 feet.

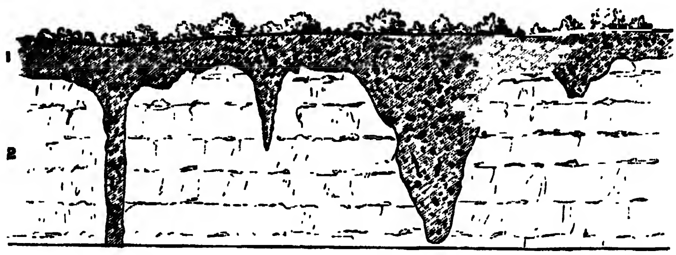

FIG. 47.—*Sand and Gravel* (1) *pipes in the Chalk* (2); *Greenhithe, Kent.*

Another effect of surface-weathering is often to show that a limestone, which at first sight may appear unfossiliferous, really consists of organic remains with a more or less pure calcareous base. The weathering, which arises, in consequence of the greater resistance offered by the crystalline structure in the fossils, causes the crinoidal or other remains to stand out in bold relief on the weathered surfaces of the rock. This is very conspicuous in the Mountain-limestone of Derbyshire; there, however, the lighter colour of the fossil renders them equally conspicuous in the body of the rock. Another instance is in the case of a band of the Carboniferous Limestone of Durham and Northumberland. Nothing is seen in the body of the dark unaltered rock; but the weathered surface is covered with small grains of the size of mustard-seed; and, when decomposition has proceeded further, a disintegrated mass of a small Foraminifer (*Saccammina Carteri*), like so much shot, results. The disintegration of a ferruginous limestone at Clifton brings to light a world of microscopic objects.

This weathering also often reveals the internal structure of the rock, showing the delicate lamination, or the false-bedding, which would not otherwise be apparent, and thus furnishes a useful diagnosis as to the manner in which these rocks have been deposited.

Winds. On a land freshly emerged from the sea, both rain and wind had necessarily an infinitely greater effect than now, when it is covered with soil and vegetation. Soft and incoherent strata were then subject to rapid wear by surface-waters; and loose materials to easy removal by strong winds, as sands now are on the coast, or on bare tracts inland, by the like cause. In the same way volcanic ashes, Diatomaceæ, and seeds are transported for distances of hundreds of miles, and so dispersed over wide areas. Sand, when carried by winds over rocks, is known to wear them smooth, and even to line their surface with scratches and furrows. In some cases,

hard rocks, such as granite, quartz, and limestone, have been polished, and quartzite pebbles worn into symmetrical forms by this means. This occurs in countries where certain winds prevail at different times of the year, so that the different sides of the pebble are alternately exposed to the wind-action. In this manner regular pyramidal-shaped pebbles have been fashioned in New Zealand and Egypt.

Dunes. The formation of dunes, and the extension of inland deserts, also originate in the action of the winds. The dunes are formed by the drifting inland of the sands on exposed shores, overwhelming the land-surface with its vegetation, houses, and farms, as they advance. On the coast of Norfolk the wind has formed sandhills 50 to 60 feet high; and so also on that of Cornwall. A remarkable case of the rapid progress of such sands, owing apparently to some temporary cause, occurred about two centuries ago on the shores of the Moray Frith, where a tract of land several miles long, and one to two miles wide, was covered with sand-dunes (the Culbin Sands) in a very few years, while little change has since taken place. A similar occurrence took place in Brittany, where a tract of ground of six square leagues was overwhelmed in the course of fifty-six years[1].

On the coast south of Boulogne, which is exposed to the strong westerly gales blowing up the Channel, the sands have formed a belt of hillocky dunes, stretching in places two or three miles inland, and at one place near Neufchatel nearly covering a chalk hill 460 feet high.

In Bermuda the trade-winds are driving the sands inland in a mass, likened by Sir Wyville Thomson to a glacier of sand, overwhelming everything before them, destroying the vegetation, entombing houses and woods, and leaving the trunks of dead trees standing upright in the midst of the sandy waste.

In the 'Landes' between Bordeaux and Bayonne the sea throws up annually 5,000,000 cubic metres of sand[2] along a coast-line of above 100 miles in length. These dunes have now an average width of 3 miles, and are advancing inland at the rate of about 3 to 6 feet annually. The sand consists of rounded grains of quartz, with a small proportion of grains of lydian stone, garnet, oligiste iron, and débris of marine shells.

In some dunes, when much shell-sand is present, the percolation of rain-water, with its carbonic acid, cements the sands into a rock hard enough to be used as a building-stone.

On these blown sands ripple-marks, resembling those on a seashore, are constantly formed; while successive layers of sand cover up the scant 'Bent' grass and the numerous land shells scattered over their surface.

[1] 'Leçons de Géologie Pratique,' p. 203.
[2] Delesse, 'Lithologie des Mers de France.'

False lamination of the sand-beds is also produced by the shifting of the hillocks, like that caused by the shifting of sand-shoals in the sea-bed.

Dr. Forchhammer has drawn attention to the extent and structure of the dunes which stretch for a distance of upwards of 200 miles along the coast of Denmark, and form hillocks from 30 to 100 feet high. These sands show ripple-marks, which are not to be distinguished from those formed by the waves on the adjacent shore; the ridges of these ripples consist of the white particles of the sand, while black particles of titanic iron accumulate in the intervening depressions. Grass and fragments of wood are found on the surface, together with oyster-shells dragged up by oyster-eating animals, and shells blown up by the winds. Dr. Forchhammer remarks how difficult it might be, in case such a deposit were submerged and consolidated, to distinguish it, with its ripple-marks, oblique lamination, and organic remains, from any ordinary geological formation[1] accumulated under water on a shore-line[2].

But the effects of winds on moving sands is not confined to coasts. The formation of deserts is a case in point. The region called the Sand Hills of Wyoming Territory is another remarkable and less known instance. These hills cover an area of about 20,000 square miles on both sides of the Niobrara River. They are composed of loose, moving sand, which is

iew of the Niobrara Sand Hills (Hayden).

blown into round dome-shaped hills, some of them scooped out by the whirling winds so as to resemble craters. These large moving bodies of sand are not uncommon in this part of Western America. In the North Park there is another large area covered with them. The strong winds that sweep over these plains will fill the air with a storm of sand, or whirl

[1] Mr. Godwin-Austen ascribed the upper part of the Lower Greensand of Guildford to this Æolian agency.

[2] 'Edinb. New Phil. Journ.,' vol. xxxi. p. 61.

it in circular columns far out of sight. The wind also throws up the sand into the most beautiful wave-like furrows. The hills are barren, but in the little intervals between there is a scant vegetation of grasses [1].

The winds also throw up on coasts, when there is little scour by currents, long lines of sand and shingle, which serve as dams to the inland waters, or they may cut off portions of the sea, and so form low-lying freshwater lakes and lagoons [2], such as those on the Mediterranean coast of France, and the few on the south coast of Devonshire. They also aid in altering the position of some harbours and in destroying others. Hastings has thus suffered in the loss of its harbours [3].

Winds may likewise affect the composition of surface-soils by carrying particles of the disintegrated rocks from one area to another [4].

Storms. Few years pass without the record of destructive cyclones ravaging some districts in tropical countries, though they are by no means confined to those parts of the world. These storms sweep over the surface sometimes in a narrow belt of destructiveness; at others spreading over widths of eighty miles or more. They are generally of short duration. They level trees or strip them of their branches, destroy cattle, and carry even heavy objects to considerable distances. They give rise also to shore-waves of the most disastrous description. In Nov. 1876 a cyclone passed over the delta of Megma in the Bay of Bengal, which apparently drove in the sea and drove back the river waters, causing a reflex wave which spread over the delta islands and extended some five or six miles inland, in a body fifteen to twenty feet high. It destroyed numerous villages and levelled one town, causing a loss of life estimated at not less than 215,000 persons. The number of animals killed was very large, buffaloes alone escaping in consequence of their being better swimmers than the rest. The dead bodies were carried backwards and forwards by the tide and ultimately swept out to sea.

Thunderstorms likewise present some points deserving of consideration as amongst possible geological agencies, or in explanation of some exceptional phenomena. In sandy strata there are occasionally found glassy tubes of variable lengths called **fulgurites.** These are formed where beds of sand have been struck by lightning; they consist of hollow vitrified tubes, descending vertically into the ground, which in some instances have been traced to the depth of 30 feet, and varying in thickness from that of a quill to ½ or ¾ inch in diameter. They are very brittle, rough, and angular, and consist of the grains of sand fused together. A considerable

[1] Hayden's 'Report of the Geological Survey of Wyoming,' 1870, p. 10.
[2] See for further information on this subject, 'Leçons de Géologie Pratique,' pp. 221–252.
[3] Dixon's 'Geology of Sussex,' 2nd edit., p. 148.
[4] C. Reid, 'Geol. Mag.' for April, 1884, p. 165.

number have been found in the dunes near Drigg in Cumberland, and at Pillau near Kœnigsberg[1].

Effects on Rocks. There has also been more rarely observed upon mountain summits a kind of vitrification of the surface of the rock, which has been attributed to the action of lightning. Saussure mentions that upon the top of Mont Blanc there is a hornblende-schist, the surface of which had been fused and covered with small dark vitreous grains of the size of mustard-seed. M. Ramond records an instance where, on the top of the Pic-du-Midi, a compact micaceous schist has had its face glazed with a sort of enamel and dotted with small vitrified globules the size of a pea. The alteration only affects the surface. Humboldt records a case where a porphyritic trachyte, on Mount Toruca in Mexico, was in places pierced with holes and covered with an olive-green glaze like that formed on some aërolites. Abich also found on the top of the Lesser Ararat an amphibolic rock superficially fused in a great number of places and converted into a sort of dark-green glass; while the rock itself is pierced with a number of fulgurites the size of a quill.

The electrical shock has also the effect of shivering and scattering rocks in a manner like that produced by a discharge of gunpowder. It is well known how church spires and other high buildings have been destroyed and the fragments of stone dispersed to some distance. In the same way mountain crags have often suffered. I saw, a short time after the event, a rock on the south side of the Pass of Brander, near Loch Awe, which had been struck by lightning, and a mass of many hundred tons, thrown down in shivered fragments on to the talus at the base of the precipice. Some years ago, a rock overhanging a valley near Salins was struck in the same way, and thrown in shattered pieces into the valley below. But, although there are many incidental notices of such effects, I cannot find any specific and detailed account. Still it is evident that it is a cause of disintegration occasionally occurring in mountainous and craggy districts.

Meteorites. The origin and constitution of meteorites will be a matter for consideration when treating of cosmical phenomena later on. We shall here merely consider them in connection with the agencies which affect the surface, and show that the falls of meteorites, which seem to most of us rare and exceptional events, are really of frequent occurrence. Were it not for the facility with which they decompose and disintegrate, meteoric stones would, no doubt, have left evidence of their presence far more widely spread on the surface of the land and on the bed of the ocean than we yet know of. The iron-meteorites are durable for a time under favourable conditions, but most stony and carbonaceous meteorites if left exposed disintegrate quickly or sometimes break up at once into dust.

[1] 'Trans. Geol. Soc.,' vol. ii. p. 528, and vol. v. p. 617.

The recorded falls of stones, of which specimens have been preserved, do not exceed about 1000. This number, however, is far from giving an idea of their frequency. M. Daubrée estimates, from the number of meteors observed on the limited portion of the earth where such observations can be made, that the annual fall in that area cannot be less than 184; and, multiplying these figures by three for the area over which the falls must escape observation, he gets an average annual fall of from 600 to 700.

The recent works of M. Daubrée[1], Dr. Flight[2], and M. Meunier[3] furnish us with a store of interesting facts respecting the recorded falls. Amongst the many we may mention the fall at Orgueil (Tarn-et-Garonne), in May, 1864, when there fell, within an oval of twelve miles in longest diameter, a shower of stones of which sixty were collected, the largest specimen weighing $2\frac{1}{2}$ lbs. At Stannern in Moravia, on the 13th June, 1819, a fall of several hundred stones occurred. One of the best observed instances, where the fall was carefully noted and recorded, is that which took place on the 26th May, 1803, at L'Aigle in the South of France, where, within an oval seven miles long, about 3000 meteorites, some approaching to 20 lbs. weight, resulted from one fall. Another very large fall occurred on the 9th June, 1866, at Knyahinya in Hungary, it being computed that over a very limited area more than 1000 stones, weighing in all from 8 to 10 cwt., must have fallen. The largest specimen, preserved in the Vienna Museum, weighs $5\frac{3}{4}$ cwt. At Puttusk in Poland, on the 30th January, 1868, a fall took place still more numerous than that at L'Aigle; of the several thousand stones that are supposed to have fallen, 950 specimens are preserved in the Paris Museum: their average weight is $2\frac{1}{2}$ ounces, and none exceed 15 lbs. At Khairpur in the Punjaub a whole cluster of meteorites fell on the 23rd Sept. 1873, over an area of 16 miles by 3; the specimens collected weighed from 3 oz. to $10\frac{1}{2}$ lbs. each.

Occasionally falls have been observed out at sea. The keepers of the Sevenstones Lightship, off Scilly, report that on the 13th November, 1872, a meteor burst over them, when 'balls of fire fell on the sea' and 'the deck of the ship was covered with cinders.' Another recent instance is recorded of a meteor which exploded near the 'Alaska' U.S.S. when off the West Coast of South America, and 'the glowing fragments of which streamed down into the sea large huge sparks and sprays of fire.'

The size of meteorites varies extremely. Sometimes they are mere meteoric dust, which, when the surface is favourable as on snow far from habitations, can be collected on melting the snow. This has been found to be the case in Greenland and elsewhere in the Arctic regions. An interesting instance has been noticed by Nordenskiold ('Voyage of the Vega').

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[1] 'Géologie Expérimentale,' vol. ii. p. 473.

[2] 'History of Meteorites,' Geol. Mag. for 1875, *et seq.*

[3] 'Géologie Comparée.' See also Mantell's 'Wonders of Geology,' 1857, p. 51.

In the upper part of the snow on a drift-ice field, in lat. 80°N., he found a number of small black grains with metallic particles containing iron, cobalt, and possible nickel; of this he gives the annexed section. Hailstones have also fallen enclosing iron particles, supposed to be meteoric, in Italy, Spain, and Siberia. Soils covering the surface of sandstone and chalk hills have likewise been found to contain traces of nickel and cobalt attributed to meteoric falls. At Hessle, near Upsala, a large number of stones fell on the 1st January, 1869, varying in size from 2½ grains to 2 lbs.; but some which were collected from off the snow and ice were of still less size.

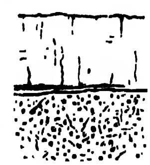


FIG. 49. *Section of Snow with Cosmic dust.*

On the other hand, blocks of very large dimensions are occasionally met with. Certain stony meteorites have been found of extraordinary size. In Brazil three are recorded of the respective weights of about 2¼, 7, and 9½ tons. At Tucson in Mexico a similar stone, weighing 1400 lbs., was found; and there is one near Durango, computed by Humboldt to weigh about 18 tons. Another remarkable instance occurs in Mexico, where, in an area of one to two miles in diameter, eight gigantic iron meteorites have been found, weighing respectively 290, 353, 430, 438, 450, 550, 580, and 654 lbs.

The depth to which meteorites penetrate the ground is generally from 2 to 3 feet; but three cases are recorded in which the penetration amounted to 8, 11, and 15 feet. At places when they fall on hard rocks they are broken to pieces and scattered.

It is evident from these few instances that the fall of meteorites may occasionally form an element for consideration in the composition, not only of the surface-deposits, but also in the sedimentary strata of past ages. Yet it is remarkable how rare are recorded geological cases. One of the most authentic instances is that mentioned by Neumann[1] in the Pläner beds of Chotzen in Bohemia. In driving a railway tunnel through beds of this age sixteen specimens of meteoric iron were found at a depth of 120 feet below the surface and enveloped in marl, which probably formed an impermeable matrix around them. The largest specimen weighed 3¼ ounces. They had a concentrically laminated structure without a vestige of crystallisation, and were composed of—

Iron . .	98·33
Nickel . .	0·61
Arsenic . .	0·32
Graphite . .	0·74

[1] 'Quart. Journ. Geol. Soc.,' vol. xiv. Part 2, Miscell. p. 22.

In most cases the decomposition of the stony, and the oxidisation of the metallic meteorites, would render them unrecognisable unless attention were specially directed to their chemical composition.

Thousands of meteorites must fall into the sea, and the discovery therefore of supposed extra-terrestrial substances in the form of cosmic dust by Murray and Renard[1] in the abysmal red clays of the great oceans is of great interest. At present, however, we are only informed that they consist of metallic spherules, and it is not clear yet how they could have escaped oxidisation.

The Effects of Weathering. The incessant operation of these various meteorological agencies on the Earth is attended by continual degradation and denudation of the surface, and the materials so removed are unceasingly undergoing distribution and rearrangement over new areas. The extent of degradation of any district is in proportion to the length of time that it has been in the condition of dry land. In England, where the land has emerged above the sea at a very late geological period (Post-glacial), the wear of the surface since that time has been comparatively small, but in older lands, which have been raised above the sea in Tertiary or still earlier times, as in parts of North America, the amount of wear assumes gigantic proportions, and the surface has been eroded and scored to an extent inconceivable in newer countries. At the same time, for these results to have ensued, certain conditions are necessary which cannot be otherwise than of local and circumscribed occurrence.

There have been, there and elsewhere, other causes that have influenced this scoring and sculpturing of the land—causes that gave the prominent reliefs to the surface, and by which the agents of denudation have been guided and directed in given lines of least resistance and into pre-existing channels. This raises the question of the extent for which each of these several causes have to be credited with the resultant effects—or how much work is to be attributed to one and how much to the other. For this object, the reader will be in a better position to form an opinion after he has studied the subject of mountain-elevation, the varied consequences of rock-pressure, and the phenomena of old river-valleys, but nevertheless it may be well briefly to illustrate our meaning.

The weathering of the hills by rain and weather is especially marked when the strata offer differing resistances to the destructive agents, and when the slopes are such as to allow of the removal of the débris. This is quite apart from the denudation produced by river- or marine-action, which may leave bluffs or isolated rocks of the harder strata, but the wear then proceeds laterally and in definite channels or lines,

[1] 'Nature' for May and June, 1884.

whereas, in weathering, it takes place superficially and vertically. Many instances of the wear produced by this cause may be seen in this country, as for example at and near Tunbridge Wells, where the sandstones present hard portions and cores which have resisted degradation, while the softer portions have been gradually removed merely by frost, wind, and pluvial action; the Brinham Rocks near Harrogate afford a very striking instance of the same phenomenon; and the Tors of Cornwall (Fig. 15) are another case in point.

But far exceeding in magnificence any other exhibition of this sort, are the bluffs, pinnacles, and buttresses of the Colorado district, so admirably pictured in the works, already referred to, of the American Geological Surveys (*ante*, p. 93), and where the process has been working in conjunction with river denudation. In that wonderful district, rocks which weather readily have yielded unequally, and are moulded into gigantic and fantastic forms of towers, spires, and terraces; and, while this sculpturing has been going on on the flanks of the cañons and in the adjacent ravines and gullies, the rain in the latter and the rapid rivers in the former are constantly carrying away the débris and incising deeper their vertical channels.

Amongst the profusion of illustration, it is difficult to choose. Possibly nothing presents a more vivid idea of this quiet and steady rain-work than the grand monumental columns of many parts of the Great West. Similar cases are well known in Europe, but they are on a comparatively small scale. The stone-capped columns of Botzen have often been described, and Lecoq figures a good instance at Boudes in Auvergne. But these, although very striking, sink into insignificance compared to those of Monument Park and other districts of Western North America. Amongst the most remarkable of these weathered rocks are those described by Dr. Hayden in the Sawatch district [1].

For about three miles along the side of South River, and for half a mile in breadth, the wooded slopes are studded with hundreds of these monuments, some of which rise to the height of 400 feet, the average being from 60 to 80 feet high. Spruce trees of great size seem like dwarfs by the side of these mighty columns, each one of which is capped by a projecting boulder of very various sizes. In this case the weathering results from the degradation of a soft conglomerate composed of a volcanic sand with trachytic boulders of various sizes. The surface waters and rain flowing over the escarpment of the valley are stayed by the blocks, and then running down on either side of them remove the soft cementing mass, but leave that which immediately underlies the boulders standing as columns, until after a time the boulder itself topples over and the column yields to

[1] 'Geol. and Geogr. Survey, Ninth Ann. Report,' 1877, p 156.

further pluvial action. Storms assist by beating against their sides and carrying away the smaller particles and the sand.

Buttress walls from 30 to 160 feet wide project from the main mass, and, where the rain and storms find in them a weak point, the wall is often perforated, and ends in the formation of an arch. That given here (Fig. 50) is one of the most symmetrical. It is about 150 feet wide and 180 feet high. The monuments in the foreground are some of them over 200 feet high. The great interest of this group is that it is formed simply and exclusively by rain-erosion and weathering.

FIG. 50.—*A View of Rhoda's Arch, Sawatch Range, Colorado* (Hayden).

Proofs might be multiplied, for no part of the surface of the land is free from the effects of this unceasing action, but it must be borne in mind that this action depends altogether on antecedent work. On flat lands it is comparatively inoperative. On the other hand, in mountain ranges, where it has been preceded by great rupture, rending, and elevation of the strata, it finds its greatest expression. It plays only a secondary part, just as the attrition on the shore produces the smooth and rounded pebble out of the angular and shapeless mass of flint; for this, however, the rude flint or sharp fragment of rock must precede the symmetrical pebble.

CHAPTER X.

UNDERGROUND WATERS AND SPRINGS[1].

Disposal of the Rainfall. Capacity of Rocks for Water. Water of Saturation and of Imbibition. Absorbent Power of various Rocks. Water-bearing Strata. Surface-percolation. Ordinary Springs and Wells. Artesian Wells. London Basin. Underground Waters. Supply to Rivers. Variation of Level in Wells near the Coast. Springs of Fresh Water in the Sea-bed. Their Limits. Delivery of Springs. Permanence of Rivers. Thermal Springs. Mineral Springs. Geysers: Theories of their Origin.

Disposal of the Rainfall. The action of the rainfall, in relation to that portion of it which runs off at once from the surface, has already been sufficiently considered in chapters V and VI. We now have to treat of that other portion of the rainfall, which passes underground and plays a no less important part in its geological bearings.

It is estimated that in these latitudes and in a country where the surface presents the ordinary variations of permeable and impermeable strata, about one-third of the rainfall is lost by evaporation, another third flows at once from off the surface into the rivers, while the remaining third passes underground to feed and maintain the underground springs. These proportions necessarily vary according to the nature of the ground,—a larger quantity running off at once into the rivers wherever the strata are argillaceous or hard and compact. In river-basins so conditioned the rivers are consequently more torrential—overflowing in winter, but often dry in summer. Where, on the contrary, the strata consist of permeable, sandy and freestone strata, or of fissured limestones, a large proportion of the rainfall passes underground, and is there stored, to be gradually returned to the surface in the form of perennial springs.

The foregoing definition, however, hardly expresses the actual case, for the river-discharge is really composed not only of the immediate

[1] On the subject of this chapter, the reader should consult the several valuable Reports (1875–1883) of the Committee 'On the Circulation of Underground Waters,' drawn up by Mr. C. E. De Rance; 'The Water-supply of England and Wales,' also by Mr. De Rance; Prof. Ansted's 'Water and Water-supply;' the several Papers by Mr. J. Lucas in the 'Proceed. Inst. Civil Engineers;' and the Report of the Royal Commission of 1869 'On Water Supply.'

surface-drainage, but also of that other portion of the rainfall which, after passing beneath the surface and remaining there for variable lengths of time, ultimately finds its way into the rivers by means of the springs just mentioned. A certain quantity of this surface-water may pass directly through the underground strata to the sea; but this only takes place on or near the sea-board, and does not materially affect the general result. The river-delivery therefore represents in fact both the rainfall at once draining into them from off the surface, and part of that which, though it passes underground, is finally, through the agency of springs, discharged into the rivers, less the portion lost by evaporation. As a consequence of these several conditions the discharge of rivers, in relation to the rainfall differs greatly in different areas, as shown in the following Table[1].

Rivers.	Area of drainage Basin.	Approximate annual rainfall.	Mean annual discharge.	Discharge per square mile of surface.	Depth run off per annum.
	Square miles.	Inches.	Cubic feet per minute.	Cubic feet per minute.	Inches.
Thames at Staines ...	3,086	26	100,000	32·40	7·31
Rhone at Avignon ...	35,745	41	3,640,000	101·33	22·86
Ganges at Benares ...	180,000	50	15,000,000	83·33	18·80
Garonne at Marmaude	20,028	47?	1,440,920	71·95	16·23
Seine at Paris ...	17,111	25	1,440,920	35·32	6·98
Saone at Trevoux ...	11,551	34?	1,018,000	88·13	19·90

While the action of the off-flowing surface-waters is, as previously shown, mainly mechanical, the action of the underground waters is more purely chemical. It is these latter which give rise not only to ordinary springs but likewise to mineral and thermal springs, and which also have been so important an agent in all those great changes of rock-structure known as *metamorphism*.

Capacity of Rocks for Water. This is a very variable property. All rocks absorb water more or less; but the quantity of available water which the strata may contain has to be looked upon as distinct from that which a rock can imbibe. The one is the portion which the rock holds until it is lost by evaporation or driven off by heat; while the other is that which passes more or less freely through the strata. The latter is the condition which prevails when the strata are below the line of permanent saturation (see p. 160); and the former is that which obtains when the rock is above the line of saturation. The one may be called the 'water of saturation;' and the other, which is held by capillary attraction,

[1] Abstract from Beardmore's 'Hydrology,' edit. 1862, p. 200.

the 'water of imbibition,' or the 'quarry-water[1].' Percolation is a property dependent on both conditions jointly.

Saturation and Imbibition. Some experiments which I formerly made[2] gave the quantity of water of saturation held in various sands, and the rate at which it passes through such strata. They show that, while the presence of a small quantity of clay does not diminish the amount of saturation, it materially affects percolation.

	Water of saturation per cubic foot. Gallon.	Percolation per hour. Cubic inches.
Thanet Sands, *fine and slightly argillaceous*	2·80	1·5
Woolwich Sands, *fine-grained, quartzose*	2·60	5·1
Upper Greensand, *slightly argillaceous, quartzose* ...	3·00	3·6
Lower Greensand, *very coarse* ,, ...	2·18	8·4
,, ,, *coarse and ferruginous* ,, ...	2·56	14·4
Garden soil	2·60	0·0

Chalk was found to absorb and hold about two gallons of water per cubic foot.

More recently M. Delesse made a series of experiments on the water held in a great variety of rocks fully saturated; the following are some of the results which he obtained with the materials in fragments.

	Water in 100 parts of rock.
Sandstone (*Grès de Beauchamp*)	13·15
Sandstone, *another specimen*	4·37
Calcaire grossier (*a calcareous freestone*), average of five specimens ...	18·03
Lower-tertiary sandstone, *pure quartzose*	29·00
Upper Chalk; *Issy*	24·10
Dark Coal-shale	2·85
Devonian limestone; *Boulogne*	0·08
Silurian slate; *Angers*	0·19
Granite (*fine-grained*); *Brittany*	0·12
Granite (*hornblendic*)	0·06
Porphyritic trachyte; *Mont-Dore*	3·70
Basalt; *Haute Loire*	0·33

M. Delesse gives the proportion of quarry-water (or, as I would propose to call it, the 'water of imbibition') of the following rocks, taken from above the line of water-level.

	Water in 100 parts.
Upper Chalk; *Meudon*	19·30
Chalk-Flint; ,, ...	0·13
Plastic clay; *Issy*	19·56
Light-green magnesian marl; *Bagneux*	27·99
Large-grained granite; *Semur*	0·37

The absorbent power of various rocks used as building-stones was also carefully determined by the Commissioners appointed to select the stone

[1] M. Delesse has used the term in a different sense. His 'water of imbibition' is the quantity held by a rock when fully saturated; and with him 'quarry-water' is the quantity retained in the rock above the line of water-level by capillary attraction.

[2] 'Water-bearing Strata,' p. 114.

for the Houses of Parliament [1]. The following are a few out of the many cases they give.

	Proportion of water absorbed by 100 parts of stone.
Limestone, Portland; *Chilmarck*	5·30
Great Oolite; *Bath*	31·20
,, *Ancaster*	18·00
,, *Barnack*	24·40
Magnesian Limestone; *Bolsover*	18·20
,, ,, *Park Nook*	24·90
Sandstone, Permian; *Mansfield*	15·10
,, Carboniferous; *Craigleith*	14·30

Mr. E. Wethered, F.G.S., has recently made a series of observations on the porosity of other classes of rocks, with respect especially to their water-bearing characters. The following are some of the results [2].

	Proportion of water absorbed by 100 parts of stone.	Gallons per cubic foot of rock.
Inferior Oolite, freestone; *Cheltenham*	23·98	1·50
,, ,, limestone; ,,	12·15	0·76
Magnesian Conglomerate; *Clifton*	5·28	0·33
,, limestone; ,,	16·33	1·02
Millstone-grit; *Bristol*	0·93	0·06
,, *Sheffield*	7·54	0·47
Carboniferous Limestone; *Clifton*	0·70	0·04
Old Red Sandstone; *Gloucestershire*	11·60	0·72
Old Red conglomerate; ,,	13·53	0·84
Old Red flags; *Caithness*	1·39	0·09

It will be seen that the quantity of water absorbed by the different strata is very variable. It is small in compact sandstones and limestones; large in soft sandstones and oolites; and largest in pure quartzose sands. But the full absorbent power of a rock, which represents both the water of imbibition and of saturation, does not represent its value as a water-bearing stratum. Clay can absorb a large quantity of water; but transmits none. Chalk absorbs freely; but transmits slowly and in small quantities. A sand of the Upper Greensand, although it held when saturated 3 gallons per cubic foot, only transmitted, in consequence of the presence of a small relative proportion of argillaceous matter, 3½ gallons per hour; whereas purer sand of the Lower Greensand, although only holding when saturated 2 to 2½ gallons, transmitted at the rate of 8 to 14 gallons per hour [3].

Laboratory experiments, moreover, are made on compact unfissured places of the several rocks, whereas in nature the chalk, oolites, and sandstones are traversed by joints and fissures, which hold and transmit water

[1] Parliamentary Report, 1839.
[2] Report of Brit. Association 'On Underground Waters,' 1882; Appendix, p. 230.
[3] See De Rance, *op. cit.*, pp. 1–22.

freely. Even compact impermeable limestones, for this reason, will form high waterless tracts, with strong springs issuing in the valleys. The value of the strata as water-bearing strata is in direct ratio of capacity of saturation, and in inverse ratio of power of imbibition. Thus, although solid Chalk and loose sands may hold the same quantity of water, the resistance to the free passage of water in the former is to the latter in the proportion of about 600:1. In impermeable strata, such as quartzites, slates, granites, clays, etc., *saturation* and *imbibition* are more or less nearly balanced.

If, with strong imbibition, the rocks are also compact, percolation is very slow, as in the case of deep-seated and undisturbed Chalk; but, if they are fissured, the cracks and fissures serve as channels and conduits to facilitate the passage of the water. In oolitic strata and soft sandstones, fissures and joints prevail as a rule.

But, while the power of imbibition interferes with percolation, it is of the highest value in its geological aspect; as, apart from free percolation, it tends to the transmission and retention of water to great depths underground, and has ever been a powerful agent in metamorphism. It is a force due in part to capillarity, and in part to the affinity of certain substances, alumina especially, for water—not chemically but hydrometrically.

Surface Springs. With respect to the annual surface percolation, prolonged experiments carefully made through depths of three feet of different materials give the following results.

	Annual rainfall of the district.	Amount of annual percolation.
[1] Surface soil; *West Hertfordshire*	26·4 inches	5·85 inches.
[2] Chalk; ,, ,, ...	26·4 ,,	9·5 ,,
[3] Sand; *East Hertfordshire*	25·8 ,,	21·4 ,,
Mean	26·2 ,,	12·25 ,,

These experiments show how very variable is the quantity of surface-water which passes underground, and how entirely it is dependent on the character of the strata.

Where a permeable stratum overlies nearly horizontal impermeable strata, as for example the beds of gravel which overlie the London Clay under London (Fig. 51), or the sands (Bagshot) overlying the same clay at Hampstead (Fig. 52) and Highgate, the rain passes downwards until stopped by the impermeable clay, on the surface of which it lodges and accumulates. When it attains a height at which the hydrostatic pressure overcomes the friction among the interstices of the constituent materials of the strata, it flows outwards, following the surface of the clay, and oozes out on the

[1] 6·232 gallons of water = 1 cubic foot.

[2] J. Evans, 'Proceed. Instit. Civil Engineers,' vol. xlv. p. 108.

[3] Greaves, 'Proceed. Instit. Civil Engineers,' vol. xlv. p. 21.

sides of the hill; or else it escapes, if it takes any determinate channel, in the form of springs, such as those which gave rise to many of the so-called 'wells' of old London, and to those on the slopes of Hampstead.

FIG. 51. *Section from St. James's Park to the foot of Hampstead Hill.*

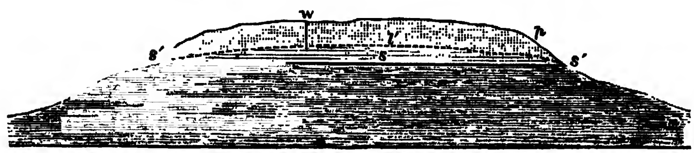


FIG. 52. *Section of Hampstead Hill.*
p. Permeable strata. *m*. Impermeable strata. *s*. Water-layer. *s'*. Spring. *w*. Ordinary surface well.
The horizontal bars represent the extent of saturation.

The escape of the rain-water lodged in *p* will be prolonged in proportion to the resistance of the materials through which it has to pass. Supposing no more rain were to fall, the water-layer *s* would eventually run out, and the springs *s'* become dry; but so long as successive rainfalls keep adding from time to time to the underground water before their point of exhaustion is reached, so long will the surface-wells *w* in *p* and the spring *s'* around *p* maintain their efficiency.

When, instead of mere cappings of permeable on impermeable strata, the permeable and impermeable strata alternate and dip in some given direction, other consequences follow. In the first case we can only have springs, and ordinary surface- and shaft-wells, with water at or near the mean surface temperature: in the second, we may have thermal and mineral springs, and artesian wells. Thus, in the section (Fig. 53), the

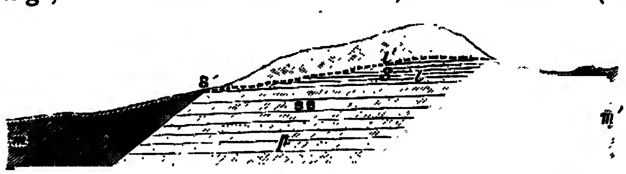


FIG. 53. *Diagram Section of the Lower Greensand Hills at Sevenoaks.*
m represents the Gault and *m'* the Wealden. *s'* indicates the situation of the springs at Riverhead.

the rainfall on the permeable strata *p* penetrates downwards, being prevented from escaping above or below by the impermeable strata *m m'*, and it passes underground as far as *p* extends without interruption. As in the course of time *p* has in all cases become filled to the brim, or to the line *l*, that water-surface gives rise to the same conditions with regard to springs as does the surface of the impermeable strata *m* in Fig. 52, for both stay the descent of the surface-waters, and the further additions, resulting from the annual rainfall, accumulate above the water-line *l* in

Fig. 53, as it does above the impermeable strata m in Fig. 52. When the underground water rises in either case to such a height above l as to overcome the friction of the constituent particles of the strata, it escapes as a spring at s'.

Artesian Wells and Springs. Further, if p or p' should be tapped at any point, however distant, below l or l', they will be found charged with water

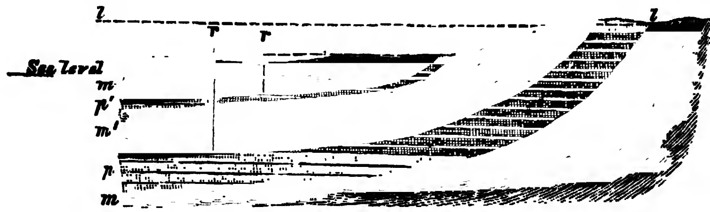


FIG. 54. *Diagram illustrating the origin of Artesian Wells.*

which will tend to rise to the level of l or l'; so that if the outcrop of the strata p or p' be at a higher level than the points where the bore holes r are made through m' and m'', the underground water will overflow and form an 'artesian well.' In the well-known instances of the artesian wells in the Lower Tertiary sands and the Chalk under London, these water-bearing strata rise from beneath the impermeable London Clay in Surrey and Hertfordshire to heights of from 100 to 300 feet or more above the level of the Thames at London, and a basin-shaped depression, much lower in the centre than at the edges, is formed, extending from Croydon on the south to Hatfield and Hertford on the north. See Pl. p. 166, Sect. 4.

Under the original normal conditions, on boring through the impermeable London Clay b, the water in c and d rose, in all the lower grounds of the Valley of the Thames, above the surface; but, owing to the multiplication of these artesian wells, and the drain upon the underground water, the inflow of the rain- and surface-waters from the outcrop of c and d cannot keep pace with the quantity removed by pumping, and consequently the line of water-level has been lowered and now stands under London about a hundred feet below the Thames level.

FIG. 55. *Diagram Section of Boxwell Spring.*—*a.* Oxford Clay. *b.* Cornbrash. *c.* Forest Marble. *d.* Great Oolite. *e.* Fuller's Earth. *f.* Inferior Oolite. *g.* Lias. *s'.* Boxwell Spring.

Where the strata are faulted and a crevice or passage exists along the

plane of the fault through which water can escape, there is produced naturally that which is obtained artificially in artesian wells, and a spring bursts out on the surface with more or less force. The great spring at Boxwell near Cirencester, which discharges one to two million gallons of water daily, is supposed to originate in this manner.

The water-bearing strata, which here supply the under-ground water, are the Inferior and Great Oolites.

To whatever depths the permeable beds *p*, *p′* (Fig. 54) may descend, there the water necessarily follows, and may in this way travel underground for miles, and reach depths of many thousand feet. In fact, it can only be stopped in its descent either by the thinning-out of the water-bearing strata,—by faults cutting them off (Fig. 55),—or by the high temperature the strata acquire at those extreme depths where the tension of super-heated steam equals the hydrostatic pressure. From whatever cause the further descent of the water is ultimately checked, as it cannot escape below ground, it follows that the permeable strata must eventually get filled by the surface-waters; and, unless artificially relieved, they must for ever remain in a state of saturation below the level of escape (*l*, *l′*) at the surface. Whether this level is that of the rivers or valleys which traverse and drain the permeable strata at their outcrop, or that of the sea-level when they there crop out, the result is that all the permeable strata become charged with water or water-logged up to those lines of level.

Any addition then made by the rainfall to the underground stores must escape or overflow either over the lip of the retaining impermeable strata *m′*, *m″*; or into the intersecting valleys where they are deep enough to trench upon the line of water-level, *l′*, as for instance in the valley of the Cray at Orpington and in the valley of the Darent at Shoreham. (Pl. p. 166, Sect. 3.) Now supposing *p* (Fig. 53) were an open reservoir, the addition made by the rainfall would at once escape at *s′*; but in the body of a range of hills consisting of permeable strata, capillary attraction, and the resistance opposed by friction to the water passing through the interstices or fissures of the strata, so retard its escape that it accumulates in the body of the hills to a height above *l*, depending on the nature and dimensions of the strata, and the distance between *m* and *m′*. The rainfall being thus retarded in its passage, instead of escaping at once, becomes heaped up and stored away in the hills to variable heights above the line of saturation *l*. This height, *l′*, depends upon the amount of rainfall, and fluctuates with it.

Consequently in the hills at a distance from valleys the line of water-level, *l′*, rises to a height considerably above the level of the valleys; but, as we approach closer to the point of escape in the valleys, this line gradually becomes lower, until as the valleys are reached, and the resist- to escape is reduced to a minimum, the water-level falls to the level of

the lowest edge of the retaining strata or to that of the valley-bottom or river-bed (Sects. 2 and 3, p. 166), where it escapes as springs.

We have thus in the body of all hills consisting of permeable strata, such as sands, oolitic strata, chalk, fissured limestones, etc., stores of water with curvilinear surfaces, reaching at their culminating point to greater or less heights above the level of the springs in the valleys; and these springs will continue to flow, so long as any portion of the underground stores continues above the line of permanent saturation (*l*), or level of the lowest point of escape. A gauge to this store is furnished by the ordinary shaft-wells, *w*, on the hills, which, to reach water, must pass below the line of variable water-level, *l′*. This line fluctuates extremely at different seasons in the year; the water, for example, in the wells on the chalk hills, at a distance from valleys, stands sometimes forty or fifty feet higher in spring than in autumn: this difference of level diminishes and ceases to exist as the points of escape at the springs are approached. While therefore the lower line (*l*) represents a line of permanent water-level or saturation, the upper line (*l′*) is a line of variable water-level, dependent on the annual rainfall; and it is the body of water (*s*, Fig. 53) lying between these two lines that constitute the underground stores or reservoirs available for the supply of our springs and rivers. Sect. 2 and 3, p. 166, are both actual sections in which the level of the water-line in the chalk hills in the London area has been proved by wells. No. 2 is transverse to the range of the Chiltern hills in Buckinghamshire, while that of the North Downs of Kent, No. 3, runs parallel with the strike of the hills.

Bournes. When in consequence of an exceptionally heavy annual rainfall *l′* reaches to the height of *l″* (Fig. 56, and Pl. Sect. 2), it gives rise to a temporary phenomenon well known in chalk districts—that is, a 'bourne.' A permanent spring, *s′*, issues at a certain point, generally low down, in a valley. At intervals of two, three, or more years it suddenly bursts out two or three or more miles further up the valley, *b*, and continues to flow for some time, when it again as suddenly ceases.

FIG. 56. *Diagram to illustrate the flowing of a 'Bourne.'*

I was at first disposed to accept the view that this might be due to some syphon-like arrangement underground, because the other cause suggested, namely, a rise of the water-line, *l′*, failed to show why the spring should not have followed the rise of the level and have gradually traversed the space between *s′* and *b*, and why it should have stayed at the point *b*. But if we consider the behaviour of *l′*, we shall see in it a sufficient ex-

planation. In consequence of an excessive rainfall this line is gradually raised *vertically* in the body of the hills to the summit level l'' without having time to expand laterally. The *horizontal* flow of the water begins afterwards and proceeds slowly owing to the friction of the rock, and it is not until after a certain time, when the height at its summit becomes sufficient to give the needed pressure, that the water extends laterally in consequence of the depression and expansion of the line l''. Then, when it reaches the point b, it escapes as *bourne* which continues to flow until all the water above the level of b has escaped and l' falls to its ordinary level, and again passes below ground.

Level in Wells near the Coast. Where the escape of the underground water is seaward other conditions obtain. Instead of a fixed level of escape, we have one subject to daily variations corresponding with the changes of the sea-level at different states of the tide. Let us suppose a tidal sea, where the hills and cliffs of the adjacent land consist of permeable strata, as for example in the Isle of Thanet, or on the coast of Brighton (Pl. p. 166, Sect. 1, Fig. 1). When, in such a case, the tide is high, it dams back the inland waters, which can then only escape at the high-tide level, s', which becomes confluent with l; but, as the tide falls to s, the inland waters are also enabled to escape at successive lower levels down to the point s; and l', as it approaches the coast, falls to l''. As the tide again rises, the line l'' rises with it, and it again reaches l. This action extends in a gradually decreasing ratio to a certain distance (d) inland, where it ceases. Consequently, in the space between d and the shore, the height of the water in all the wells (w' w^2) will fluctuate with the rise and fall of the tide, the difference being greatest in those wells, w^1, which are the nearest to the shore, and not felt at w^3.

It results also under these conditions of the proximity of the permeable strata to the sea, that, as the inland underground waters are always maintained by the rainfall in the body of the hills at a level higher than the sea-level, the hydrostatic pressure of a body of water of the height of l, l', as in Sect. 1, and Fig. 1, tends constantly to force the fresh water outwards, and to stay the influx of the sea-water, thus causing a permanent flow of the inland waters seaward, where it escapes as springs between the tide levels. This outward flow can only be altered by exhaustion, as in the case of excessive pumping,—say at w^2, where the well has been carried below the level, l, of the inland waters,—when the current becomes reversed, and the sea-water will flow in to restore the normal level of l. Otherwise, however near the coast a well may be, the sea-water under ordinary circumstances never flows in, even though the difference of level of land and water be but small, as in the case of Coral or other such islands.

Submarine Springs of Fresh Water. Where the inland stores are large, and the variable line l' rises high above the sea-level, the hydro-

static pressure may be so considerable as to overcome, down to certain depths, the resistance of the column of sea-water, whether on a tidal or a tideless coast, and, in the absence of other channels of escape, drive out the fresh water into the sea-bed at *h*; where, owing to its lighter specific gravity, it will rise with more or less force, depending on the volume of water and force of ejection, to the surface (*s′*, Fig. 57). It is thus that we have on many coasts, especially on the limestone coasts of the Mediterranean, strong springs of fresh water rising in the midst of the sea at a distance from the shore[1].

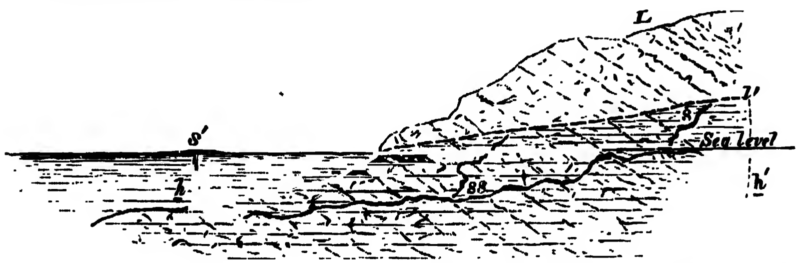


FIG. 57. *Diagram-Section of a Limestone Coast (as for example at Nice or Spezia).*
L. Fissured limestone hills. *s* and *ss.* Fissures serving as water-channels. *s′.* Fresh-water spring rising through and above the salt water.

There are, however, limits to this action. The specific gravity of fresh water being 1·00, and taking that of sea-water at 1·0297, a column of sea-water 1000 feet high will counterbalance a column of fresh water nearly thirty feet higher, but not more[2]. Therefore, when the ratio between *h s′* and *h′ l′* is in this proportion, no outflow of fresh water can take place, as the pressure of the two columns is equal, but with unequality of pressure the submarine springs increase in force. Where there are high hills near the coast, it is possible to have fresh-water springs at considerable depths beneath the sea; but where the coast is low such springs cannot exist; nor can they, as has been here suggested, occur at any very great depths or distance from land, in consequence of the want of an inland body of water of sufficient height, and of the increased friction.

Delivery of Springs. It is found that the time taken by the rainfall on the higher Chalk hills (as in centres of Sect. 2 and 3) to reach the line of variable water-level, *l′*, is from three to four months; so that the winter rainfall raises the water in the wells to its highest level in spring or early summer; and the droughts of summer are most felt in autumn or early winter. It is further estimated that it takes, in the case of the Hertfordshire Chalk hills, about sixteen months for the underground water to travel from the central area to its outlet in the perennial springs which

[1] These springs are sometimes so charged with carbonate of lime, that the deposit of calcareous matter serves to cement the loose sands and shingle into a compact rock.

[2] The friction of the passages in the rock takes off from the full effect of this difference.

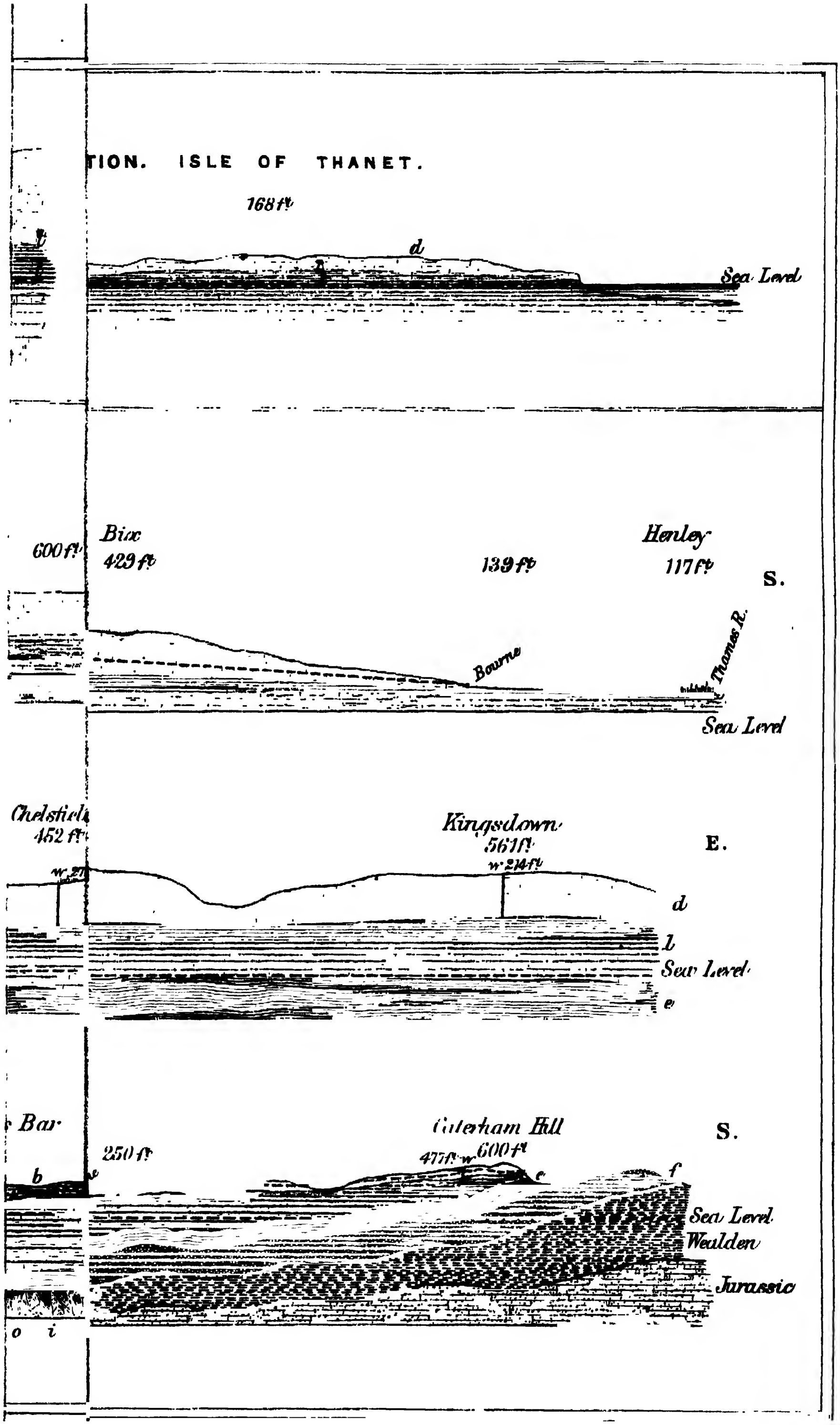
feed the river Lea. That is to say, supposing no rain fell for sixteen months, it would take that time before all the springs of those underground water-stores were exhausted.

It is these subterranean reservoirs which exist in all hills consisting of permeable strata, that give volume and permanence to our rivers. So long as any store of underground-water remains in the hills above the line of permanent saturation, so long will the perennial springs continue to flow and contribute to the maintenance of our rivers; and, as in these latitudes the rainfall is rarely intermittent more than a few weeks at a time, fresh supplies of this surface water are being constantly added to the underground springs, whereby they are maintained in efficiency and action, only varying in volume according to the annual rainfall.

Thermal Springs. Below the line of permanent water-level, *l*, the permeable strata, *p*, Figs. 53, 54, are, as just mentioned, in a state of permanent saturation, and will continue so unless the water be drawn off artificially by artesian wells, or naturally by fissures or faults in the superincumbent strata. As also, to whatever distance underground permeable strata may range, the surface-waters follow,—and further as the temperature of the crust of the earth increases with the depth at the rate of about 1° Fahr. for about every fifty feet of depth,—any waters obtained artificially or naturally from deep-seated strata will bring with them to the surface the bathymetrical temperature of the strata from which they rise. Thus, for example, at Paris, where the mean annual temperature is 51° Fahr., the water of the artesian well of Grenelle, which travels about 100 miles underground, and rises from a depth of 1800 feet, has a temperature of 82° Fahr. In the great boring at Sperenberg, near Berlin, which is carried to the exceptional depth of 4172 English feet, the temperature of the water from the depth of 3390 feet is 110·5° Fahr.

Thermal springs in non-volcanic districts, such, for instance, as at Bath and Buxton, may generally be considered as natural artesian wells, where water, after descending through permeable strata to great depths, escapes through fissures in the overlying strata (the sides of faults or dislocations) to the surface. The temperature of such springs, above the mean of the surface, is necessarily proportionate to the depth reached by the descending water; and, as the Bath waters have a temperature of 120° Fahr., we may assume the depth from which they rise to be about 3500 feet.

Mineral Springs. Water, when cold, takes up little except the salts of lime and magnesia; but under heat and pressure its action becomes much more energetic and it dissolves many other mineral substances. Therefore thermal springs are generally mineral springs, varying according to the nature and depth of the strata. When the strata are calcareous,



TION. ISLE OF THANET.
168 ft
d
Sea Level
600 ft
Bix
429 ft
139 ft
Henley
117 ft
S.
Bourne
Thames R.
Sea Level
Chelsfield
452 ft
Kingsdown
561 ft
w 214 ft
E.
d
l
Sea Level
e
Bar
b
250 ft
Caterham Hill
477 ft
600 ft
e
f
S.
Sea Level
Wealden
Jurassic
o
i

and much carbonic acid is present, an extra quantity of carbonate of lime is taken up, as in the Clermont and other such hot springs. Amongst the most remarkable calcareous springs are those at Hammam-Meskhoutin near Constantine, where a number of copious natural fountains (utilised by the Romans) issue from the ground. They have a temperature of 203° Fahr.; and as the water cools and evaporates, it deposits the excess of carbonate of lime in a circle around, and so forms a small basin. The water overflowing the edges of these basins keeps gradually adding fresh deposits, and has thus built up in the course of time columns or rather huge beehive-shaped masses, in some instances twenty-six to thirty-two feet high,—at which height, owing to the ascensional power of the water failing, the columns cease to grow[1], and the water bursts out at other spots, where the same process is repeated and new deposits formed. Thus a number of such columns have risen, covering a considerable space of ground, as shown in the annexed sketch[2], in which however the volume of water is made too large.

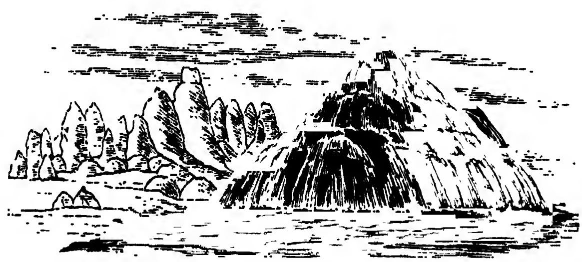


FIG. 58. *View of the hot springs of Hammam-Meskhoutin.* (Reduced from M. Niel's sketch.)

One of the finest exhibitions of this deposit of Travertine from hot springs is that of Hierapolis in Asia Minor. The springs issue on the mountain side, and flow down the slopes in a series of cascades which constantly change their position. The whole ground has been covered with beautiful white incrustations, which have taken the form of basins, stalatitic columns, arches, etc. Hamilton describes the scene as though the water had been suddenly arrested and petrified in the act of leaping from rock to rock, and states that under the travertine lie buried the ruins of many of the old buildings and temples of Hierapolis which surrounded the springs, the temperature of which he estimates to be about 100° Fahr. (see Fig. 59, p. 168).

When the underground-rocks consist of granites, syenites, etc., or contain mineral veins, the water, under the heat and pressure to which it is subjected at great depths, acts upon and decomposes the silicates present in the constituent minerals of these rocks, and takes up, in addition

[1] Somewhat similar but smaller mounds, much covered and hidden by grass, are said to exist in parts of Australia, and also in Persia.

[2] 'Bull. Soc. Geol. de France,' vol. xi. p. 129, and 2nd ser., vol. ix. p. 624.

to the lime, the more soluble salts of potash, soda, iron, lithia, and other substances contained in those minerals. It is the presence of these salts, due to this cause, that gives to so many of the springs of France and Germany their peculiar character and value. A certain number of the saline waters of Germany, as also some in our own country, are, however, merely artesian brine-wells of artificial construction (see also Chapter XIX).

In England there are few thermal and mineral springs. They are numerous in the granitic and extinct volcanic district of Central France (Auvergne); again on the great lines of fault in the Pyrenees; and are especially common in some of the Central States of Germany.

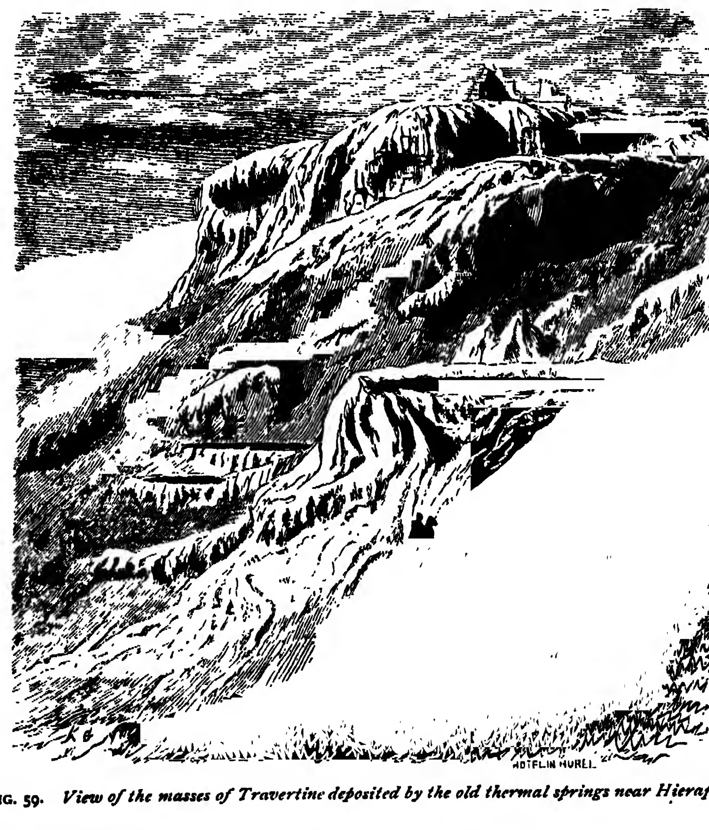


FIG. 59. *View of the masses of Travertine deposited by the old thermal springs near Hierapolis.*

Geyser Springs. There is another class of springs, which, though associated with volcanic phenomena, are in reality due to the causes we have just been considering, only modified in their mode of action by the proximity of volcanoes, and forming siliceous instead of calcareous deposits.

The geysers of Iceland are situated in a plain or valley at the foot of a range of hills, about thirty miles distant from Hecla. They are inter-

mittent hot springs, and vary in activity. The Great Geyser has formed a siliceous mound or depressed cone, about 40 feet high and 200 feet in diameter, having on its summit a basin, 7 to 8 feet deep and 50 to 60 feet wide. In the centre of the basin there is a pipe or tube, 10 feet across, and descending vertically to a depth of 74 feet. The mound consists of a white siliceous sinter, with which the basin and pipe are smoothly lined. The water in the basin is beautifully limpid, and has a temperature of from 160° to 200° Fahr. At intervals of from 12 to 30 hours subterranean noises are heard, great bubbles of steam rise to the surface and explode with increasing frequency, and the water in the basin rises over the brim. Suddenly a column of water is projected upwards, others of greater height succeed, ending after the eruption has lasted a few minutes with a more violent explosion, when a magnificent jet of water, accompanied by volumes of steam, is thrown up to a height of from 100 to 150 feet. The level of the water then falls 7 or 8 feet or more in the tube; and it is some hours before it regains its former level.

The Strokkr, which is only a short distance from the Great Geyser, has a pipe flush with the ground, 8 feet in diameter, and gradually tapering to a depth of 44 feet. The water at the surface is here always boiling. The eruptions are as high as those in the Great Geyser, and take place more frequently. There seems to be a close connection between the two springs. There are many smaller geysers, some active and some extinct, spread over a space about 5 miles long by ½ to 1 mile wide. The times and force of eruption at the several geysers have been found to vary considerably during the last century.

The first explanation suggested to account for the curious phenomenon of the geysers was that underground cavities (*h*, Fig. 60) existed in the lava, into which the surface-waters percolated, and where the water was exposed to a temperature higher than that of the boiling-point. It was supposed that as steam was generated in *h*, it gradually forced down the water to the level of the channel *c*, and up the pipe opening on the surface; until the water in the reservoir *h*, falling below the level of *c*, the high-pressure steam rushed out violently and by successive efforts ejected the column of water in the pipe.

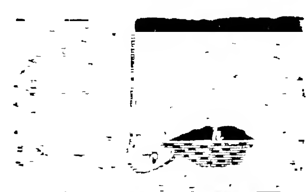


FIG. 60. *Diagram of a Geyser.* (After Mackenzie.)

M. Robert[1], however, found on trial that the temperature of the water in the pipes of the geysers increased with the depth, and might therefore, with a relief of pressure, flash suddenly into steam. Similar experiments instituted subsequently by Descloiseaux and Bunsen gave

[1] 'Bull. Soc. Géol. France,' vol. xi. p. 338.

more detailed and exact results. They showed that, although the temperature increases with the depth, it does not increase in proportion to the pressure to which the water is subjected, so that the boiling-point under those pressures was not reached. The temperature also was found to vary before and after an eruption [1].

Four hours before a great eruption.		*Nine hours after a great eruption.*	
Height from bottom.	Temperature.	Height from bottom.	Temperature.
22·85^m	85·0° C.	22·85^m	85·0° C.
19·55	85·2	19·20	82·6
14·75	106·4	14·40	85·8
9·85	12[illegible]·4	9·60	113·0
5·00	123·0	4·80	122·7
0·30	127·5	0·30	123·6
Mean temperature	108·33°	Mean temperature	102·30°

Descloiseaux estimated that the boiling-point of water, under the pressure of a column of the height (74 feet) and density of that filling the tube of the Great Geyser, should be 136·15° C., whereas observation gave only 127 C., or a difference of 9·15° C. He suggested that the constant additions of fresh increments of heat from a distant heating source eventually raises the temperature at bottom to above that of boiling-point, and that when the tension exceeds the pressure, the water flashes into steam and causes an eruption. Bunsen, on the other hand, suggested that the eruption might be due to oscillations in the column of water. Thus on the left of Fig. 61 are given the observed temperatures taken a few minutes before an eruption. At 30 feet from the bottom, at *A*, the water had a temperature of 121·8° C., whereas its boiling-point under the pressure there would be 123·8° C. If the column be then lifted 6 feet, and the water at *A* transferred to *B*, it is there at a level where it should boil at 120·8° C., so that, as its temperature is now 1° C. in excess of boiling, steam should be instantly generated and an eruption ensue. Prof. Tyndall adopts this view, and illustrates it by an ingenious experiment in which he heats, under given conditions, the lower part of a tube filled with water, when shortly the water is spasmodically expelled in a succession of jets [2].

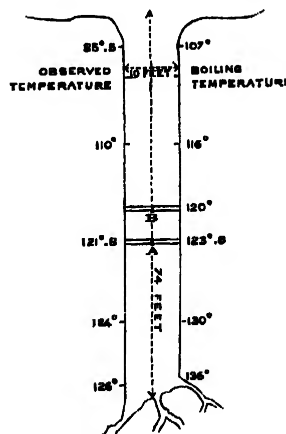


FIG. 61. *Diagram section of a Geyser.* (After Tyndall.)

I would add one remark to this, based on the hydro-geological

[1] 'Bull. Soc. Géol. France,' second series, vol. iv. p. 550.

[2] 'Heat a mode of Motion,' 6th edit. p. 168.

conditions of the ground. The tube, which is emptied by an explosion, at once fills again, although often very slowly[1]. It is evident that there is a body of underground water the level of which tends to rise to near the top of the tube, *a*, Fig. 62; let us assume also for the moment that the heat at the bottom of the tube (or of its roots) is sufficient to raise the temperature of the water above that of the boiling-point at that depth. After an explosion, which lowers the level of the water in and around the tube, the water from the higher levels of the surrounding rock flows into and refills the tube. This water, which is cooler than the water discharged, has its temperature in the upper part of the column gradually raised by convection currents, while at the same time the temperature at the bottom of the tube is kept below its normal by the same cause. But when after a time the water in the upper part of the tube is so heated that the convection currents no longer sufficiently refrigerate the bottom water, that water then rises above the boiling-point, and rapidly acquires a tension, which causes it to flash into steam and eject the contents of the pipe[2]. This is preceded by slight explosions of steam, as, from time to time, a convection current superheats some small portion of the column. This alternate refrigeration by cooler water, combined with a variable rate of percolation, and with some differences in the underground temperature, affects necessarily the periods of eruption.

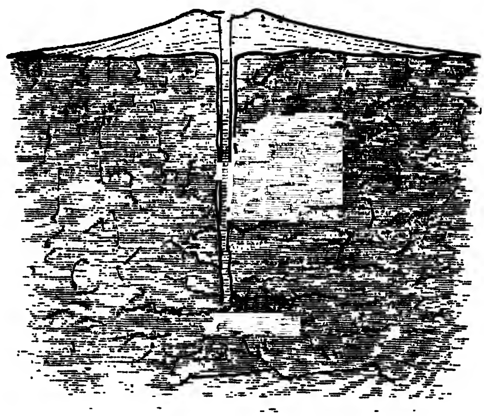


FIG. 62. *Diagram of a Geyser Spring.*

Similar geyser phenomena are exhibited in the Yellowstone-river District of America on a scale of still greater grandeur. The eruptions are more frequent, and in some instances the water is projected to a height of 200 feet or more. It is estimated that, taking the geyser-springs of all sizes, there are not fewer than 10,000 of them in that remarkable district. The following views (Figs. 63, 64) represent two of those geysers, one before and another during an eruption.

[1] Originally many of the geysers (and apparently some few still) had more the character of overflowing (natural artesian) springs. With the building up of the mound they become intermittent.

[2] It is owing to this that the clods of turf thrown into the tube of the Strokkr Geyser, by checking the convection currents, raise prematurely the temperature of the bottom water and provoke an early explosion.

All the geyser-waters hold in solution considerable proportions of silica derived from the action of the superheated water under pressure on the silicates of the volcanic rocks. The water of the Great Geyser of Iceland contains in 100,000 parts—

Silica	51·90
Carbonate of soda	27·47
Chloride of sodium	26·38
Sulphate of magnesia	0·91
" soda	1·80
" potash	13·43
Sulphur	0·36
	122·25 (Damour)

while 100 parts of the siliceous sinter, or geyserite, consists of—

Silica	87·21
Alumina and iron-peroxide	1·25
Lime	1·71
Soda and potash (traces)	0·66
Water	8·90
	99·73 (Damour).

There is a certain analogy in the results between the hot springs of Hammam-Meskhoutin and the geysers of Iceland. But, while the latter

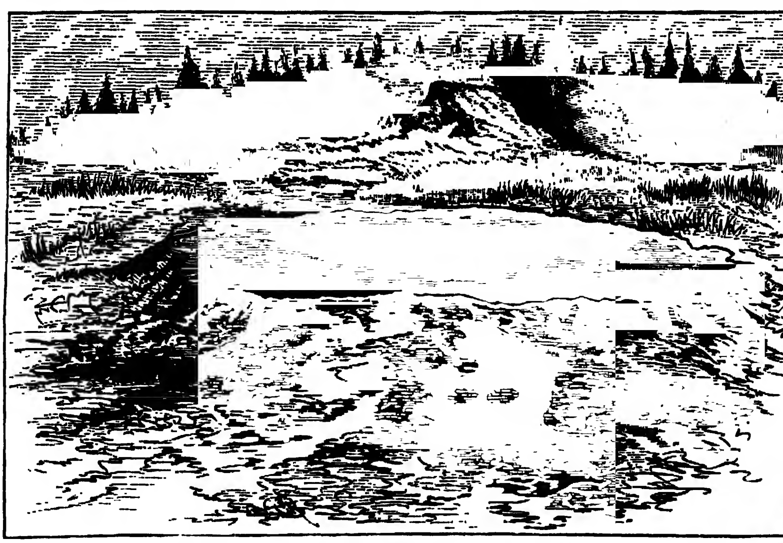


FIG. 63. *View of Castle Geyser and Fire Basin.* (Hayden, 1873.)

are in the midst of a volcanic district, the former are at a distance from any such influence, the surrounding strata consisting of Tertiary marls, limestones, and sandstones. They both lie on gentle slopes at the foot of hills, and the action in both is clearly of old date, and had originally artesian characters. The overflow from the Icelandic geysers deposited great beds of siliceous sinter, extending for a distance of five miles with

a breadth of half to one mile, while the North-African calcareous springs have formed a stalagmitic deposit, covering one to two square miles of surface. On these floors rise, in one instance, the depressed siliceous mounds of the geysers, and, in the other, the calcareous hummocks of the old Roman bath-waters.

But, while the waters of Hammam-Meskhoutin pass underground from the outcrop of the strata in the adjacent hills to a depth where the temperature is acquired by depth alone, those of the geysers pass probably direct from the neighbouring hills under an old stream of doleritic lava which seems to have filled up a former valley. The surface-drainage, which once may have formed a brook at the bottom of the valley, now forms a water-level at depths in the lava, through the crevices of which it at first rose to the surface at points below the level of intake, and deposited the great sheet of sinter now covering the ground. With the rise of the ground by deposition, as well in the Icelandic as in the African area, of the respective precipitates, the overflow became impeded; but while in the latter case, where hydrostatic pressure is the only cause of efflux, the escape-pipes changed their position as soon as they reached a height that pressure became insufficient, the former have had their existence prolonged by the heat connected with volcanic agency, which has kept up, as it were, a series of blow-holes, in which the original overflow is supplemented by the spasmodic explosions due to a local and high degree of heat.

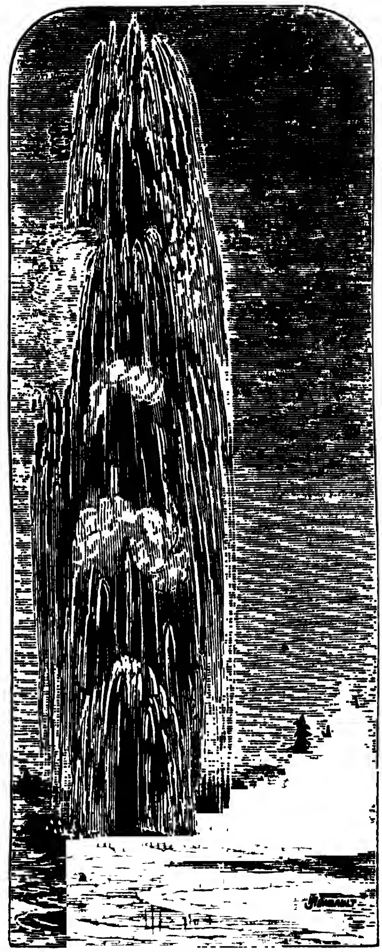


FIG. 64. *View of the Giantess Geyser, 250 feet.* (Hayden, 1871.)

The hot springs on the river Waikato, in New Zealand, are also very striking. They issue on the slope of a hill and fall over successive terraces of white siliceous sinter to the valley below. The basin at top overflows continually, but only exhibits slight and occasional geyserian action. They bear amongst siliceous deposits a similar relation to the geysers that amongst deposits of calcareous matter the springs of Hierapolis bear to those of Hammam-Meskhoutin.

CHAPTER XI.

ICE AND ICE-ACTION.

THE SNOW-LINE. ORIGIN OF GLACIERS. THEIR DIMENSIONS. MOVEMENT OF GLACIERS. ABLATION OF THE ICE. FORMATION OF MORAINES. ABRASION OF THE ROCKS. ROCHES MOUTONNÉES. DESCENT OF GLACIERS. GLACIER WATERS AND LAKES. THEORIES OF GLACIER-MOTION: AGASSIZ, HOPKINS, FORBES, TYNDALL, MOSELEY. ALPINE TEMPERATURES. EXPANSION OF ICE. PRESSURE. PLOUGHING ACTION OF THE ICE. FORMATION OF ICEBERGS. CARRYING POWER OF FLOATING ICE. TRANSPORT OF ROCKS AND GRAVEL BY ICEBERGS. FLOE- AND SHORE-ICE. ICE-FOOT. RIVER-ICE. GROUND-ICE.

THE chemical and mechanical action of water in its geological bearings having been discussed, let us now consider some of its physical properties. These relate to the effects of—

1st. Snow and glaciers; 2nd. Sea-borne ice; 3rd. River-borne ice.

The Snow-line. The decrease of temperature in ascending from the sea-level is at the rate of about 1°F. for every 300 feet of ascent. The line of perpetual snow is 16,000 feet above the sea-level at the Equator, and gradually descends towards the poles. At the Peak of Teneriffe it is about 13,000 feet high; in the Sierra Nevada of Spain 11,000 feet; in the Pyrenees 9200; the Alps 9000; Norway 5000; Lapland 3300; at Beeren Island 600 feet; and on the North-West Coast of Spitzbergen, in lat. 79° to 80° N., it nearly reaches the sea-level.

The snow-line does not follow the level of the mean annual freezing-point; at the Equator it is rather above it; in the Alps it is 7°, and in Norway 11°F. below it: while further north it rises above it. It is in fact dependent upon the mean temperature of the summer rather than that of the entire year; and it is besides dependent upon a number of local influences, such as exposure to certain winds, proximity of the coast, etc., so that it is often higher on one side of a mountain-chain than on the other. On the south side of the Himalayas the snow-line is 13,000 feet, and on the north side 16,600 feet above the sea-level.

Origin of Glaciers. Above the snow-line the snow tends to accumulate on the surface and by its weight to travel down the slopes. At first, in the higher altitudes, it is dry and powdery, and drifts before the wind. In passing to lower levels, the mass becomes exposed to greater alternations of temperature, and under the influence of the sun's rays the separate flakes are partially thawed, and on freezing again are transformed into so many grains of ice. This is called *névé* or *firn*. The water which slowly drains through these from the upper layers gradually cements them

together but without filling all the interstices, while at the same time the whole mass becomes more and more compressed by its own weight, and finally forms a semi-compact granular mass. As one winter's snow-fall succeeds another, successive layers are formed, and as the mass travels downwards in the valley-channels it becomes more compact, and finally passes into the state of glacier-ice. But whatever the solidity, transparency, and beauty of the bulk of this ice, it still retains traces of its origin—in its granular confused crystalline structure, its occasional soil- and air-bubble bands, and stratiform appearance. It is not until this massive glacier-ice, which flows as a frozen river, has passed to a considerable distance below the snow-line, that it gradually yields and melts before the increasing heat.

Dimensions. In Switzerland the glaciers have been estimated to attain a thickness of from 500 to 1000 feet; but this is only an approximation. They vary in length from 5 miles in the Aar glacier to 14 miles in the case of the Aletsch glacier, with a medium width of from ½ to 1 mile; while amongst the Himalayan glaciers that of Biafo has a length of 35 miles. But these measurements sink into insignificance compared with the great glaciers of the Arctic regions. In Greenland, even at the front edge, where they break off into the sea, they are said to attain a thickness of 2400 feet; and the great Humboldt Glacier has a breadth of not less than 115 miles; while on the coast further north these dimensions are even surpassed. Their length is yet unproved. Rink travelled on the inland ice-sheet 70, and Nordenskiöld 123, miles into the interior, where they saw no limit to the great ice-fields before which they had to retreat.

Movement of Glaciers. The glaciers of Switzerland move downwards at a rate varying with the seasons, the rainfall, and the slope. In Switzerland the Glacier du Bois advanced 258 feet one year, and as much as 470 feet in another year. The glacier of the Aar advanced 486 feet in two years [1]. In winter the movement of the glacier is much less than in summer. Tyndall estimates that the motion of the Mer de Glace is then about half of what it is in summer.

According to Agassiz, it would take two centuries for the glacier of the Aar to run out, and three or four centuries for an object placed on the longer Aletsch glacier, near its source, to reach its lower end.

The motion of the ice is not uniform throughout its mass. It is greater towards the centre than on the sides; and greater in its upper than in its lower surface; thus in all respects resembling the flow of a river. The rate of flow in different parts of its course depends on the gradient. Tyndall found it to be 20 inches a day for the Mer de Glace above Montanvert in summer, and 33 inches per day below Montanvert.

Ablation of the Ice. The entire surface of the glacier is subject to a constant decrease by evaporation, and as it descends below the snow-

[1] See Agassiz's 'Études sur les Glaciers;' Forbes's 'Travels in the Alps;' and Tyndall's 'Glaciers.'

line the whole mass gradually melts. If, owing to a continuation of winters of lesser severity or summers of greater heat, the melting should go on at a more rapid rate than descent, then there is a retreat of the glacier, such as has been now going on with the glaciers in Switzerland for the last twenty or twenty-five years.

Professor J. Forbes found that the ablation, as it is termed, between June and September in 1842 lowered the surface of the Mer de Glace 24½ feet, and in some exceptional cases the lowering in summer has been found to be as much as 1 foot a day. The effects of this evaporation from the surface of the ice is well illustrated by the ice-stalks left under the large isolated blocks of rock shown scattered over the glaciers (Fig. 65).

Moraines. The sides of the steep rocky valleys through which the glaciers descend are incessantly weathered and wasted by the alternations of heat and frost to which they are exposed. The rock fragments falling

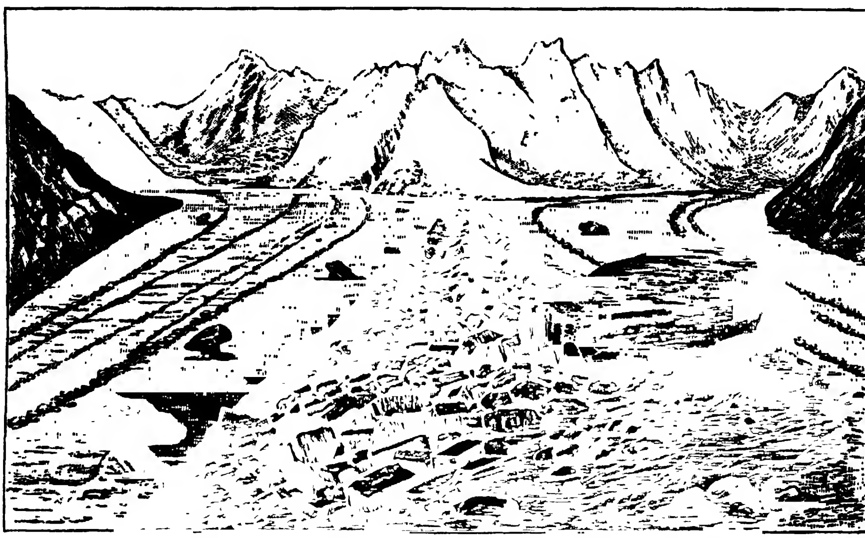


FIG. 65. *View from the medial Moraine, looking up the Aar Glacier.* (Agassiz.

on the sides of the glacier form taluses (the lateral moraines) which move down with the glacier. When a second glacier coming down from another pass, joins the first, two lateral moraines become confluent and descend on the united glaciers in a central line, which is called the medial moraine (Fig. 65). These moraines finally reach the end of the glacier, where they are discharged and form, together with the loose débris pushed forward by the under surface of the glacier (the *moraine profonde*), the 'terminal moraine.' These latter moraines form mounds, stretching in front of the glacier, from a few feet to many yards in height (Fig. 66).

Abrasion of the Rocks. The rock fragments, some of them many tons in weight, carried down on the surfaces of the medial and lateral

moraines, undergo no friction, and retain all their original sharpness and angularity; but those which travel under the glacier, where the friction

Fig. 66. *Terminal view of the Zermatt Glacier, with polished 'Roches moutonnées' on the left.* (Agassiz.)

is great, are generally small, worn, and scored on all sides. These latter consist in greater part of the stones which have fallen from the

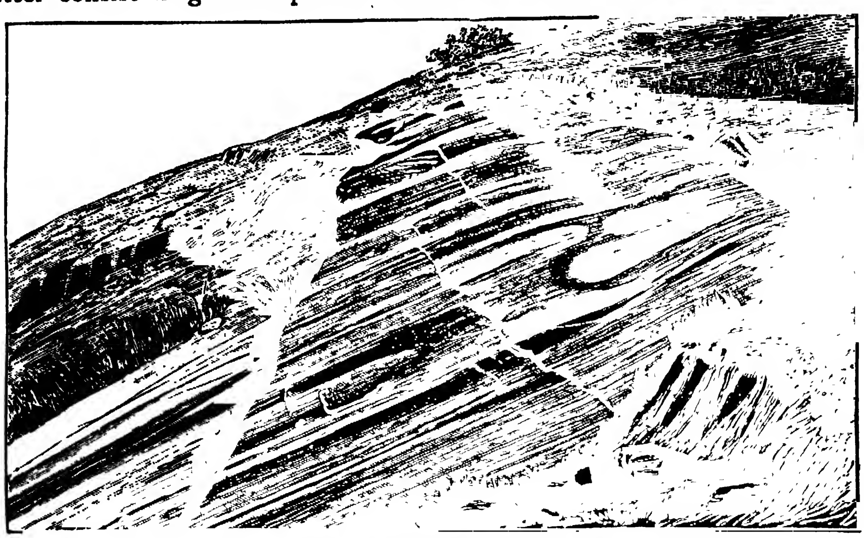


Fig. 67. *Polished Rocks on a mountain surface.* (Agassiz.

surface into crevasses and gradually worked their way to the bottom, where, held and pressed down by the overlying ice, they have rasped with

it over the rocky glacier-bed. The powerful abrasion has rounded the edges of these loose fragments and ground them down (for they are liable to turn over repeatedly from the motion of the glacier as it descends) by wear against the underlying rocks. At the same time the harder of these stones, which are fixed, like gravers' tools, in the ice, groove and indent with long continuous scratches (striæ) the underlying rock-surfaces over which they pass; while the fine sand and finer silt, resulting from this wear and abrasion, act like emery powder, and give the rock over which the ice passes a smooth and polished surface (Fig. 67). The effect is powerful in proportion to the pressure, and more conspicuous on certain rocks than on others—for example, limestones and granites are remarkable for the fine bright polish they take.

As the result of this process not only are the rocks underlying the glacier planed and worn down, but all their sharp angles are removed; and, where the resistance is unequal, small smooth dome-shaped eminences, generally polished, and striated in the direction of the ice-movement, are formed. These are called *roches moutonnées;* and, while always presenting a continuous slope in the direction from which the ice travels, they often retain their scraggy edges at the further end, under the lee of which a certain amount of débris finds shelter and forms a short trail. This form of structure is known as 'crag and tail,' and serves to indicate the direction of the ice-movement on old glaciated surfaces.

FIG. 68. *Diagram of 'Crag and Tail.'*
← *Direction of Ice Movement.*

As the terminal moraine in front of a glacier contains both the angular, unworn fragments fallen from the steep precipices bounding the glacier in its course from the high central ridges, together with the ground, worn and scratched fragments held and carried down in the bottom ice over the rocky bed of the glacier, this moraine consists of a variable proportion of rough angular fragments with a certain proportion of worn and striated fragments (Fig. 69), the relative numbers varying of course according to the character of the country traversed. The surface débris, so abundant on glaciers of temperate climates, is of much rarer occurrence amongst the ice-fields and glaciers of the Polar regions.

The limit of perpetual snow in the central Alps is at a height of about 9000 feet, but the glaciers in the valley of Chamouni descend to the level of 3500 feet, and in the valley of Grindelwald the glacier descends to 3225 feet above the sea-level. In some equally warm or even warmer latitudes

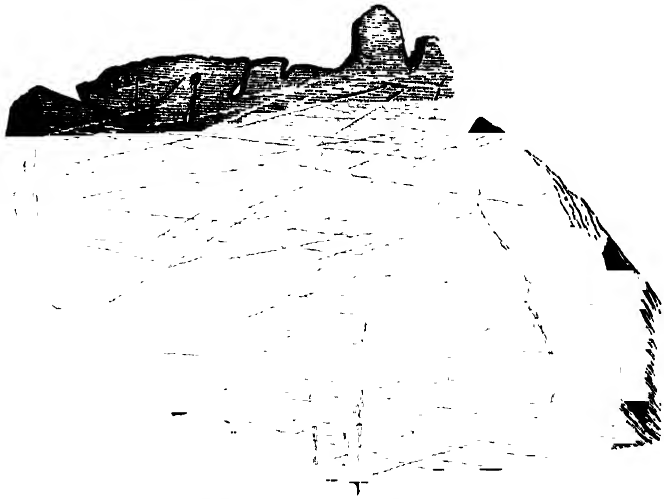


FIG. 69. *Ice-scratched fragment from an Alpine Terminal Moraine.*

glaciers descend still lower. There are glaciers in New Zealand, in lat. 42° to 46° S., which come down to within 2000 to 3000 feet of the sea-level, and one even comes down to under 800 feet, discharging its load of débris and blocks in the midst of a subtropical vegetation.

Glacier Waters. The gradual melting of the glaciers furnishes the head-waters of many streams and rivers. A body of water constantly issues from beneath all glaciers (Fig. 66). It is derived partly from springs, partly from surface-waters higher up the glacier, and partly from the melting of the ice caused by friction on its bed. The water is charged with an extremely fine light-grey sediment, formed by the constant abrasion of the rocks, which gives a peculiar milkiness to the waters that is retained for a long time. This silt forms a deposit of stiff loam or clay of a bluish-grey colour, in marked contrast with the yellow and ochreous deposits of open river-waters. This is partly owing to the lesser oxidisation of the iron in one case than in the other, and may also be in part owing to the fact that the one is the result of actual erosion, whereas the other is due to the surface decomposition and disintegration of the rocks.

Water sometimes lodges on the surface of a glacier and gives rise to small streams which are ultimately lost down some of the numerous crevasses. Where the ice is more compact, instances occur of small lakes being formed on its surface.

Glacier Lakes. In the Alps this surface-water is met with on a few of the glaciers in the shape of pools, generally small ('baignoires' of Agassiz), though some of them attain the size of from 20 by 20 to 20 by 40 mètres in length and breadth. They move with the glacier, and drain sometimes suddenly through fissures, while at other times they last for years. A remarkable one, attaining the dimensions of a small lake, has been described by Dolfuss-Ausset. It was noticed in 1842 on the Aar glacier, near the confluence of the Thierberg glacier. It then had a superficies of 10 acres, with a depth of 206 feet, and was surrounded by steep cliffs of ice over which glacier-detritus was constantly tumbling and gradually filling up the lake. As showing how compact some glacier-ice may be, this small lake lasted twenty-four years, and was carried a distance of 600 feet at a rate of about 25 feet annually before it disappeared.

In the Himalayas, lakes of this class are not uncommon. Sir Joseph Hooker noticed one part of the Kinchinjhow glacier where it was half a mile wide and the surface very undulating, which he found covered with large pools of water, one of them being 90 feet deep.

But it is in the part known as the Mustakh range that these lakes are most numerous. In Colonel Godwin-Austen's account of that range many such bodies of water are described. On the Pumnah glacier, where the surface is either a succession of ridges more or less stony, or where in other places it resembles 'a sea of frozen waves,' 'small pools of emerald-green water' fill many of the hollows, and are surrounded with cliffs of ice; elsewhere there are streams of running water which often end abruptly by discharging down some crevasse. On the Bahio glacier there are hollows filled with water forming lakes often as clear as crystal and of great depth. Some of these lakes measured as much as 500 yards in length and from 200 to 300 yards in breadth; and were spread over a distance of more than two miles along the centre of the glacier, which was there very level [1].

As the glaciers in the main valleys advance below the snow-line, if they pass lateral valleys which have no glaciers, they dam back the waters of these valleys and thus give rise to small lakes. Of this the Merjelen See is a notable instance. Much more dangerous are the lakes formed by glaciers from lateral valleys descending into and traversing the main valleys. In these cases a greater body of water accumulates behind the glacier, while the glacier itself is smaller and weaker. When these lakes burst and sweep away their barriers the effects are most devastating, as in the instances of the inundations of the Drance in Switzerland and the Skardo in India. Lakes are also formed when the glacier retreats and leaves a sufficiently large and compact terminal moraine to dam back the drainage-waters of the glacier.

[1] The author in 'Phil. Trans.' for 1879, p. 694.

Theories of Glacier Motion. This has been the subject of much and long discussion. Louis Agassiz supposed that the motion was due to the infiltration of water into the fissures, cavities, and minute crevices in the ice, and its subsequent freezing within the glacier; and that this produced an expansion of the mass by which the glacier was pushed forward.

Mr. W. Hopkins considered gravity was the main cause, since all glaciers in motion appear to repose on surfaces of sensible inclination to the horizon. The least mean inclination of the bed of any glacier in motion is about 3°, which gives a fall of about one foot in 20.

Neither of these hypotheses, however, explained how the ice is held together and adapts itself to the inequalities of its channel. To account for this, Professor James Forbes supposed ice to be capable of changing its form under the pressure to which it is subjected, in a manner similar to that which in a *viscous* mass changes its form under the same circumstances. It was found that the central portions of a glacier move considerably faster than its lateral portions, just as a viscous mass would move along a trough inclined at a small angle to the horizon; and, moreover, it was obvious that the general mass of a glacier did so change its form as to accommodate itself to the changing dimensions of the valley down which it moved.

Professor Forbes also found that the upper surface of a glacier moves faster than the lower surface. In one instance it was shown that the upper part moved twice as fast as the lower part. It was concluded there were two motions, one due to sliding, and the other to viscosity.

An experiment of Faraday's, who had observed that two pieces of ice in perfect contact would freeze together so as to become one perfectly continuous mass, though the surrounding temperature should be much higher than 32°, suggested to Professor Tyndall an explanation of a remarkable property of glacier-ice. He proved by further experiments the extreme facility and rapidity with which a piece of common ice, after being crushed and broken into numberless fragments, will reunite into one continuous mass of transparent ice. It is this process, which has been termed 'regelation,' that re-cements and holds together the glacier-ice, notwithstanding the rending and fissuring to which it is subject. For ice, although plastic under *pressure*, is not so under *tension*: and this is the point which the theory of plasticity did not explain. While a viscous body, like bitumen, may be drawn out in filaments by tension, ice, far from stretching in this way, breaks like glass under this action.

Canon Moseley considered heat to be the cause of motion. He observed that a sheet of lead placed on a plane surface, inclined less than would enable it to slide by gravitation alone, yet tended nevertheless to move downwards when subjected to changes of temperature. The cause of this

is that, when the lead dilates by an increase of heat, gravity opposes its upward motion, while it facilitates the downward motion. When the temperature is lowered the lead contracts; and here again, in consequence of gravity, the strain is downwards. Consequently, with every change of temperature, there was a slight displacement of the lead downwards, with a force such that the nails with which it was fastened were drawn out of the wood. Canon Moseley contended that an action analogous to this was the proximate cause of the descent of glaciers; that the dilatation and contraction of the ice produced by the passage of the sun's rays into it could, on the inclined surfaces on which it moved, have no other than progressive downward movement.

Alpine Temperatures. One of the chief objections urged to Canon Moseley's hypothesis was that the air, even at high altitudes, did not reach the freezing-point in the month of July; and consequently that the range of temperature was not within the limits to affect the expansion of ice in the smallest degree. But this objection was based on old observations of temperature. I find that the more recent and elaborate observations of Dolfuss-Ausset give different results[1], for they show that the highest and lowest temperatures in the shade during the summer months at the station of St. Theodule, 3333 mètres (10,932 feet) above the sea-level, are as under:—

	Highest day temperature.	Lowest night temperature.	Mean day.	Mean night.
June	52·0° F.	11·0° F.	33·5° F.	28·5° F.
July	58·5	14·5	36·0	30·0
August	59·0	14·0	36·5	31·5
September ...	48·0	19·0	37·0	31·0

The greatest difference between the day and night of the same twenty-four hours in August was 14° F. The radiation during night is also excessive. Dolfuss-Ausset states that it lowers the surface of the snow to 18° F. below that of the air. It would appear from this, therefore, that there are nights in summer when the surface of the upper ranges of the glacier may be reduced to below 0° F., and that there are few or no nights but what it may descend below freezing-point.

This seems a sufficient answer to the objection; and, notwithstanding the rather low conductivity of ice, which is still, however, equal to that of the softer argillaceous and calcareous strata, if we take into account how greatly the volume of ice varies with temperature, the heat-hypothesis seems to offer a highly probable solution of the problem.

Expansion of Ice. For, according to the experiments of M. Brunner, before referred to (p. 139), the contraction of ice is not only greater than that of rocks, but it is greater than that of any metals. To take, for

[1] 'Matériaux pour l'Étude des Glaciers,' vols. vii. and viii.

example, the co-efficients of linear expansions of lead and iron as compared with ice for 1°C.

Ice	0·0000375
Lead	0·0000301
Cast iron	0·0000112

It would appear from this that the gain in length of a mass of ice of given dimensions by changes of temperature is more than three times greater than that of iron.

An increase of temperature of 5°F. in a block of ice two miles long would therefore give a linear expansion of about 12 inches. This is not only an irresistible force, which can only have a downwards push, but it is also a force which the temperature-changes must maintain in more or less constant operation[1].

Equally important in the heat-hypothesis is the stress caused by contraction. This indeed is the complementary action needed to produce the steady advance of the glacier; for in contracting, owing to friction of the bed and gravity, the pull, as shown by Canon Moseley, can only act downwards. If for example a given length of glacier were to expand 12 inches, that expansion takes place in the direction of least resistance, or downwards, then, on a contraction subsequently of similar amount, the 'pull' acting again in the same direction, will also bring forward and downwards the upper section of that segment of the glacier.

The observations before made (*ante*, p. 140) on the ice of the Arctic American lakes bear on this question, inasmuch as they show how large the contraction produced by cold is, and how greatly ice expands with a rise of temperature. The fissures, for example, that are made in the ice of Lake Winnipeg by severe cold are from 2 to 3 feet wide, narrowing towards the bottom where the temperature is higher. These fissures then fill with water which soon freezes. With warmer weather the whole mass expands; and in some small lakes the expansion of the ice which ensues before the end of the season is such that it forces the ice in ledges up the shores of the lake.

Pressure. While variations of temperature bring into action an expansive force which, combined with gravity, drives the glacier downwards and forward, the pressure, when the ice is of great thickness, exerts a vertical crushing force tending to compress the mass: but to this is opposed the shearing resistance. The force needed to overcome this resistance has been very differently estimated. Much depends upon the length of time, and much upon temperature. The conditions in the laboratory are very different to those under which glacier-ice itself is placed, and the shearing force of 75 lbs. per square-inch estimated by

[1] The enormous mechanical force shown in the expansion of even small bodies of ice, in bursting pipes and splitting strong iron shells, is an old and well-known experiment.

Canon Moseley has been much questioned. If however, as he supposed, the expansion of ice by heat is the principal factor in the motion of glaciers, then the action of expansion will lessen as the depth increases and the influence of external changes of temperature decreases; and, as the same cause which affects the whole mass and leads to its downward movement must affect all the parts, so the upper layers will tend to move faster than the lower ones and to move or slide forward one over another, and this cause should assist the crushing force in overcoming the shearing resistance. The shearing force will also lessen as the temperature of the surrounding medium rises, so that the lower the glacier descends the more plastic the ice becomes, owing to the higher general temperature allowing of freer movement amongst the particles of ice.

In considering the motion of glaciers, it would therefore seem necessary to take into account very various causes. We have in the expansion of the ice by heat during the day, and by freezing of water during the night, sources of pressure in constant operation. Combined with this is the downward stress caused by contraction of the ice by cold and the tendency to move or slide downwards by gravitation—a tendency assisted by the melting of the ice on its bed by terrestrial heat and friction. But these causes only impart motion; plasticity and regelation are the important elements which direct the flow, and, holding together the brittle mass of ice, cause it to adapt itself to the changing dimensions and ever-varying slopes of the glacier channels.

Ploughing Action of the Ice. The rock-erosion produced by a glacier depends on its weight, gradient, and channel. So long as it moves in a given channel with bounding walls which prevent dispersion of force, so long will the glacier rasp the surface of the rocks over which it moves and plough up the ground in front of it. There is, it is clear, a not inconsiderable amount of erosion still going on under existing glaciers, the streams which flow from under them always being turbid and the rock-fragments worn; but it is also certain that the extremely eroded channels, down which existing glaciers move, are the channels down which the vast glaciers of the Glacial Period moved, and therefore that much, if not nearly all, of the effects of the excessive glaciation now visible in the glacier channels is due to the past and not to the present ice-action.

When a glacier debouches from a narrow valley with a steep gradient into a main valley or plain, where the gradient is small and where the ice can expand fan-like in several directions, it would seem that the erosive or ploughing power is greatly diminished or lost, though it may continue to carry forward and maintain a frontal moraine.

Charpentier mentions that on one occasion the Glacier du Tour, in the Valley of Chamouni, descended into that valley, and advanced a dis-

tance of 80 feet over a bed of gravel. When, at the end of five years, the glacier retreated the gravel was found to be undisturbed, and even the tufts of Alpine plants on its surface were found in their place. It has also been observed, with reference to the Norwegian glaciers, that the ploughing action has been rather exaggerated, and that the snout of the glacier, though it ploughs out a little of the materials in front of it, *rises over the rest.*

Formation of Icebergs. When the glaciers descend to the sea-level, as they do in Spitzbergen, Greenland, and the Antarctic lands, they move forward over the sea-bed; and, when the water is deep enough, the end of the glacier, pushed forward till it overhangs, breaks with the strain and falls with a crash into the sea, where it is carried away by the tides and currents as an iceberg[1].

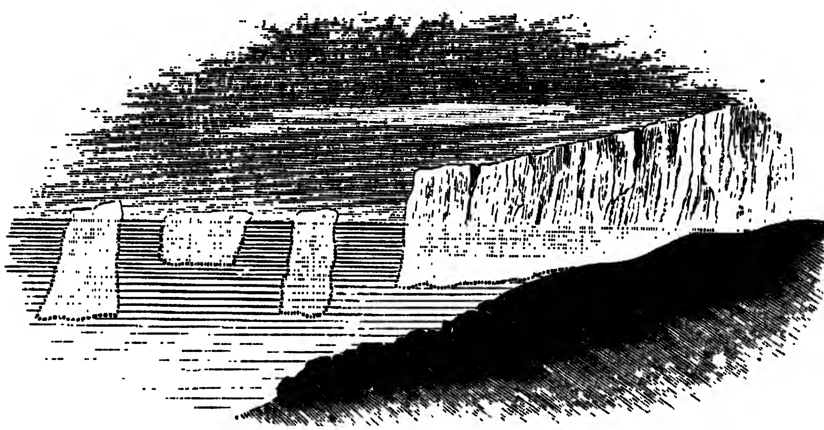


FIG. 70. *Diagram section of a Greenland Glacier discharging Icebergs.*

With the ice also is carried away any moraine débris strewed over the surface of the glacier. In Greenland and Spitzbergen this may occasionally happen; but in the Antarctic regions, where the land is swamped by one vast ice-sheet and few rocks are exposed, the icebergs rarely carry rocks or débris unless on the under side. The whole of central and northern Greenland is under ice and snow which cover mountains rising to considerable heights. So far as the interior of the country has been explored—and Nordenskiold has penetrated inland to a distance of 123 miles from the coast—great rolling plains of compact ice and snow, with here and there pools and streams of water, extend everywhere beyond sight, and not a rock nor a pebble is to be seen.

Icebergs vary greatly in their size, in accordance with the size of the glacier from which they are derived. They mostly rise 20 to 50 or 100

[1] The glacier may also be buoyed up, or segments may slide off.

feet above the surface of the sea; but occasionally some of much larger dimensions have been met with. In the North Atlantic they are sometimes 500 to 600 feet high. But it is in the Antarctic ocean that they attain their greatest size; they have there been seen of heights of 500, 600 and 700 feet; and some have been said to be even 800 to 1000 feet high. They vary also in length,—some being a few hundred feet, others from one to two miles or more long. The icebergs of the North Atlantic are in general rugged and pinnacled; whereas a large proportion of those of the Antarctic waters are vast tabular masses, some of which are four miles in length[1].

Carrying Power of floating Ice. It is easy to realise the enormous floating and transporting power of such great bodies of ice. Pure water attains its maximum density at the temperature of 39.2° F. Below this point water expands until it reaches the freezing-point, when its density falls from 1·000 to 0·999873. In freezing the water suddenly expands; and, taking water as unit, ice at 32° F. has a density of 0·920; and a given mass of water in passing into ice gains $\frac{1}{11}$th in volume. Consequently, while a cubic foot of fresh water at 60° weighs $62\frac{1}{2}$ lbs., a cubic foot of ice weighs only $57\frac{1}{2}$ lbs. But, as the density of sea-water at 32° is 1·0297, a cubic foot of it weighs 64 lbs., so that sea-water has a much greater floating power than fresh or river-water.

Thus, while the difference in weight between a cubic yard of fresh water and a cubic yard of ice is 135 lbs., the difference between that bulk of ice and sea-water is 182 lbs.; and while in the former case 100 cubic yards of ice could carry a weight of 6 tons, in the latter case it could carry a weight of 8 tons; so that a berg 1 mile long, 500 feet deep, and 3000 feet wide, could carry above twenty million tons of rock.

It is sometimes asserted that if a berg stands 100 feet out of water, there is a depth of 900 to 1000 feet below water; but, owing to the greater density of sea-water, and glacier-ice being lighter than ordinary ice in consequence of the presence of more or less air-bubbles, it may often be a question whether instead of only $\frac{1}{10}$th or $\frac{1}{11}$th, as much as $\frac{1}{6}$th or $\frac{1}{7}$th part of the iceberg is not above the surface of the water. Then, again, much depends on the shape of the berg; so that in pinnacled icebergs the depth of the ice below water may possibly often be not more than 3 or 4 times its height above water. The calculation should be for bulk, not height.

Transport of Rocks and Gravel by Icebergs and Floes. With regard to the amount of débris actually borne by icebergs the evidence is somewhat conflicting. On the one hand, we are told by competent and experienced observers that on the many bergs they have met with in crossing the Atlantic they have never seen a stone. On the voyage of the

[1] Ross's Voyage, and Moseley's 'Challenger.'

'Challenger,' during the time the ship was in the Antarctic seas, many icebergs were seen, but on none of them could moraine matter or rocks be detected. Dr. Wallich remarks on the scarcity of rocks and gravel on the bergs of the North Atlantic in about 60° N. lat.; and M. Charles Martins

FIG. 71. *Old Berg, with Boulders, fifty yards in diameter.* (Kane.)

says that, during the two voyages of 'La Recherche' in the seas of Iceland and Spitzbergen, they never saw any blocks carried by floating ice.

On the other hand, Darwin records two instances of the occurrence of angular blocks of rock on the bergs of the Antarctic seas; and Sir John Ross and Admiral Wilkes, who approached nearer to the Antarctic lands, mention several instances in which they saw dirt, stones, and boulders on the surface of icebergs in the same seas. Rocks and stones are frequently recorded by Scoresby, Kane, and many other observers on bergs in the North Atlantic, Davis Strait, and Baffin's Bay.

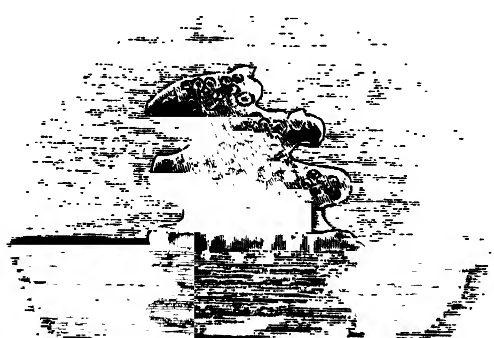


FIG. 72. *Berg honeycombed with Boulders and stained with syenitic débris.* (Kane.)

Captain Inglefield, in returning from Davis Strait in 1850, reports that at one time 180 icebergs were counted from the Crow's Nest, and that several were of gigantic dimensions and bore rocky burdens of *many tons weight*. Again, in the seas between Spitzbergen and Franz-Joseph's Land, Lieutenant Payrer saw, in lat. 79° N., icebergs laden with dirt; and, on another occasion, others whose surfaces were covered with rock débris. He also states that in long. 71° E. they saw a large iceberg about 60 feet high, and on walking over it they came across *two moraines lying on its surface.*

It is probable that in those cases where no rock débris has been

seen on icebergs, the bergs were far from the parent glaciers; but that, when seen nearer to the glacier-lands, the presence of dirt, rocks, and stones is of more frequent occurrence. The fact may be that the bergs have in some instances changed their centre of gravity and turned over; or portions may have broken off; but the more constant and sufficient cause is no doubt the melting of the surface as the glaciers float into warmer latitudes, together with the action of rain and storms. These must sweep and wash off the surface the loose débris they carry, especially as, in all probability, the great bulk of the débris would, where they are remnants of the lateral moraines of the glaciers in which they originated, lie on the outer edges of the icebergs.

FIG. 73. *Boulders on side of Iceberg.* (Kane.)

Not only do icebergs scatter gravel and blocks over the floor of the sea near and far, but, where they become grounded, they must plough up and disturb the sea-bed, while at the same time they deposit around the spot a large part of the stony débris with which they may be loaded. In shallower waters the grounding of the ice disturbs and detaches large fields of seaweed, which rise to the surface, and, as described by Dr. Sutherland, float down Davis Strait at certain seasons of the year. Their stems are often found abraded, and their roots likewise contain shells and other animal remains which have suffered from the violence of the action by which they have been liberated. The same observer also remarks on the trituration and grinding of the sea-bed thus effected; and he further notices that icebergs, when grounded, are frequently subjected, from being unequally pressed upon by passing floes, to a rotatory motion, which must cause deeper indentations and greater wear of the submarine beds.

Floe- and Shore-ice. But the most common means of boulder-transport probably are not the great glaciers descending from frozen and snow-covered lands, but the shore- and floe-ice formed on the coasts of those lands. The ice formed by freezing of the Arctic seas does not exceed 5 to 10 feet in thickness, but on the coast, where it becomes packed, it rises in long and rugged mounds and ridges, 30 or 40 feet or more in height, to which the loose shore débris underneath becomes attached. In other places, where high cliffs overhang and the water is deeper, a belt of ice is formed at the base of the cliffs by the freezing of the water and the drifting of snow, which is known as the ice-foot. It is this ice, which receives on its surface the angular débris detached from the

overhanging cliffs, that forms so important an instrument of transport in Smith's Sound and Baffin's Bay.

Kane, speaking of the great ice-belt seen from Cape James-Kent, says 'that it was covered with millions of tons of rubbish, greenstones, limestone,

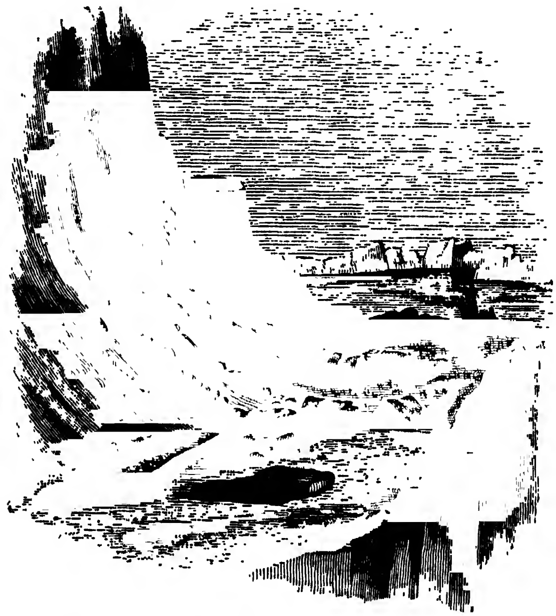


FIG. 74. *The Ice-foot at 'Cape James-Kent,' Smith's Sound.* (Kane.)

chlorite-slates, rounded and angular, massive and ground to powder.' Its importance as a geological agent struck him with much force. Upon the thin frozen waters of Marshall Bay he recognised raft after raft of last

FIG. 75. *Raft of Belt-ice with Boulders.* (Kane.)

year's ice-belt which had been caught by the winter ice, each one laden with its heavy freight of foreign material. Summer heats and bergs and floes driving against it detach the ice-foot from the coast, and carry away the

growth of years. These heavily-laden rafts of coast-ice, owing to their smaller size, cannot travel so far as the larger glacier bergs. They are sooner lost, and the foreign materials they carry are less widely distributed than those of the other ice-masses.

The floe-ice also, when driven by winds and currents on to the shore, either ploughs up the shore shingle into heaps[1], or where the shore is bare and rocky it abrades and planes down the rocky floors of the strand.

An illustrative instance of the transporting power of ice, and of the distance and rate of travelling of floe-ice, is furnished by an incident which took place a few years since, when the 'Hansa' was abandoned on the east coast of Greenland. A portion of the crew with their boat and goods, in the whole forming a considerable cargo, sought refuge on the ice-floe. On the breaking up of the ice in the summer, the mass on which they were was carried southwards by the current, and at the end of nine months had drifted to a distance of about 1300 miles from where they started. By this time the mass of ice was greatly reduced in size, and threatened submergence, when they were fortunately rescued.

River-ice. This is of two descriptions. First, that which is formed on the surface of the water; secondly, that which freezes on the mud and stones at the bottom. It is the latter especially, together with that which forms on the sides of rivers, that serves to transport stones and boulders. In these latitudes the effects so produced are unimportant; still, in this country, stones are occasionally removed and carried lower down the rivers by ice-action.

Among the few cases that have come to my knowledge, was one where two blocks of stone, of the size of the largest paving-stones, were frozen in the shore-ice at Grays in Essex, and when the ice broke up were carried down the Thames to some miles below Gravesend. It is possible even that in severe winters, such as that of 1776, when most of the great rivers of Europe were ice-bound, and the ice off Havre presented the appearance of a frozen Baltic; or in 1788, when the sea on the shores of the Channel was in places frozen for a considerable distance from land, that there might have been seen in these latitudes some of the phenomena connected both with river- and with sea-ice, which we usually consider confined to northern latitudes alone.

The transport of blocks by ice in rivers of cold climates has often been described[2]. Captain Bayfield[3] mentions how, both on the lakes of Canada and in the St. Lawrence, he has seen fragmentary rocks carried away by ice. The St. Lawrence is low in winter, and the loose ice, accumulating on

[1] The shore of Arctic North America has been described as presenting at one part in summer a succession of small gravel hillocks extending for miles in length.

[2] See Lyell's 'Principles of Geology,' 10th edit., vol. i. p. 364.

[3] 'Proc. Geol. Soc.,' vol. ii. p. 223.

the extensive shoals which line each side of the river, is frozen into a solid mass, being exposed to a temperature sometimes 30° below zero F. The shoals are thickly strewed with boulders, which become entangled in the ice, and in the spring, when the river rises from the melting of the snow, the packs are floated off, and frequently convey the boulders for great distances.

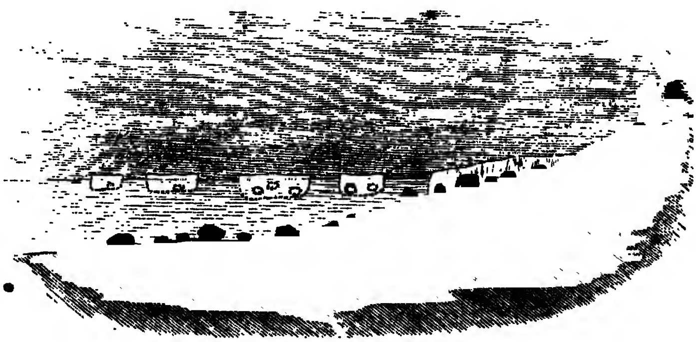


FIG. 76. *Diagram to illustrate the transport of Boulders by River-ice.*

Sir William Logan describes the curious effect caused by the packing of the ice during some winters at Montreal, owing to the sudden rise in the river caused by the damming back of its waters by barriers of ice. When one of these is formed it is rapidly increased by extensive fields of drift-ice. The ice becomes piled and packed, and, assisted by the accumulation of snow, the whole becomes frozen into a solid body, sometimes more than 20 feet thick; this, when the waters suddenly rise, is lifted and urged forward with terrific violence, heaping the rended masses on the banks of the river to the height of 40 to 50 feet. Buildings are endangered even to a distance of 200 feet from the river-bank. In one instance a warehouse of considerable strength and magnitude was pushed over by the great moving sheet of ice as though it had been a house of cards [1].

Not only does river-ice transport stones and boulders and level obstacles on the banks, even to some height above the ordinary river-level, but land animals may also be caught and frozen in the ice, and their remains carried to a distance and buried in the river or estuarine drifts. M. Huc [2] relates a curious instance of this sort. When on the banks of the Mouroni Oussou, a large river in Thibet, he saw on the ice a number of black objects ranged in single file across the river. On approaching he found that these objects were the heads of more than fifty wild buffaloes encased in the ice. They were, he supposes, trying to swim across the

1 'Proc. Geol. Soc.,' vol. iii. p. 766; 'Quart. Journ. Geol. Soc.,' vol. ii. p. 422.
2 'Voyage en Thibet,' vol. ii. p. 219.

river at the moment it was freezing, and were caught and destroyed by the floating ice. The heads of these animals with their great horns were alone above the ice, whilst their bodies were visible beneath in swimming posture.

Ground-ice. When in cold climates the rivers are at the same time rapid, the temperature of the water may, owing to the movement between the particles of the water, be reduced to several degrees below freezing-point before ice is formed. In these cases, if there be any sharp points, such as rock or shingle at the bottom of the river, such points will present surfaces whereon the water will crystallize or freeze, just as a sharp point will determine incipient crystallization in any saturated saline solution. Ice in these cases is gradually formed on the bed of the river, and when its buoyancy causes it to rise to the surface, it brings with it the loose stones and other objects to which it was attached.

This process is of constant occurrence in the rivers of severe climates, such as Siberia and Arctic America. This ground-ice, or anchor-ice as it is also called, tends by this dredging process gradually to deepen the bed of a river, whereas the action of the surface- and shore-ice rather tends to widen and render more shallow the river-channels.

In the Meuse it has been observed that blocks of ice 1 to 2½ feet thick form in severe winters for considerable distances in shallow and gravelly parts of the river-bed; and these on becoming detached from time to time carry away pebbles and stones to lower reaches of the river. Even in the Neva at St. Petersburg, where the river is 50 feet deep and 1500 feet broad, ice forms there in contact with its bed, and this is said to rise to the surface in the spring if not previously thawed. Ice has been often noticed to form at the bottom of all the rivers in Siberia, and it is stated by Baron Wrangel, that its sudden rising to the surface in early winter causes so rapid a consolidation of ice, that in a few hours the rivers become passable in sledges instead of in boats. He also says that the masses of ice contain a quantity of gravel and weeds. When the thaw sets in, the ice lets fall its load at places far distant from whence they came. Many instances of the formation of ground-ice, though on a smaller scale, have been recorded in this country since attention has been drawn to the subject. Enough, however, has been said to show the importance of it as a geological agent[1].

[1] 'Phil. Trans.' for 1864, pp. 293-295.

CHAPTER XII.

VOLCANOES.

DISTURBING AGENTS. VOLCANOES; THEIR FORM AND STRUCTURE. CHARACTER OF ERUPTIONS. LAVA-FLOW. LAVA-LAKE OF KILAUEA. HEIGHT; NUMBER; AND POSITION OF VOLCANOES. SIZE OF STREAMS; ETNA; HAWAII; ICELAND. COMPOSITION OF LAVA. INCIDENTAL MINERALS. VOLCANIC VAPOURS. ASHES. SUBMARINE ERUPTIONS. EFFECTS OF HEAT. SECONDARY MINERALS. COLUMNAR STRUCTURE. CAUSE OF VOLCANIC ACTION. SCROPE'S HYPOTHESIS; MALLET'S; DAVY'S. THE PRESENCE OF WATER. THE VAPOUR OF WATER THE SUPPOSED CAUSE OF ERUPTION. OBJECTIONS. EVIDENCE OF THE PRESENCE OF FRESH AND SALT WATER. UNDERGROUND WATERS. EXHAUSTION OF SUBTERRANEAN WATER. INFLUX OF SEA WATER. PRIMARY CAUSE OF ERUPTION.

Disturbing Agents. The agencies which have contributed to the building up of the sedimentary strata, and the surface changes to which the various rocks are subject, having been described, it remains for us to consider the subterranean agencies whereby these strata have been disturbed, the original planes of deposition altered, and large submarine tracts raised into continental areas and mountain-masses. Of these forces the Volcanoes and Earthquakes of the present period are the exponents, indicating the nature, but not necessarily the degree of intensity or activity of the forces formerly in operation.

Volcanoes are mountains or hills with a spreading base, but always more or less conical at top, and ejecting from time to time vapours, ashes, and lava, from a central opening called a crater. The cinders or ashes are thrown upwards to great heights, and in falling they build up a conical elevation round the vent or crater. Amongst the looser ejected débris there are interstratified beds of lava, which have either flowed out of the central vent, or from fissures in its side and lower down on the base of the mountain.

The central cone always presents steep sides (about 30°), but the lower slopes are often prolonged at very small gradients (6° to 10°), and extend to considerable distances from the central crater. Vesuvius, with a height (in 1868) of 4247 feet, has a base of 8 miles in diameter; and Etna, which is 10,834 feet high, has a base of about 40 miles in diameter.

The following outlines show the general proportions, after nature, of two active volcanoes and of one recently extinct volcano:—

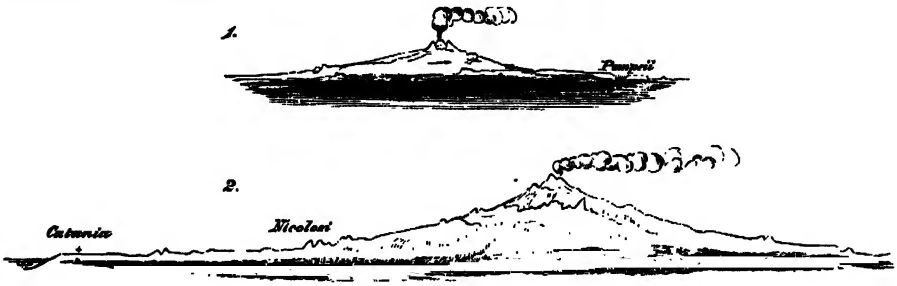


FIG. 77. (1) *Vesuvius*, (2) *Etna*, *and* (3) *Cantal with restored outlines.* (C. Prévost.)

After the force of an eruption is spent, a slight discharge of vapour and scoriæ may go on for months or years, and gradually build up a smaller

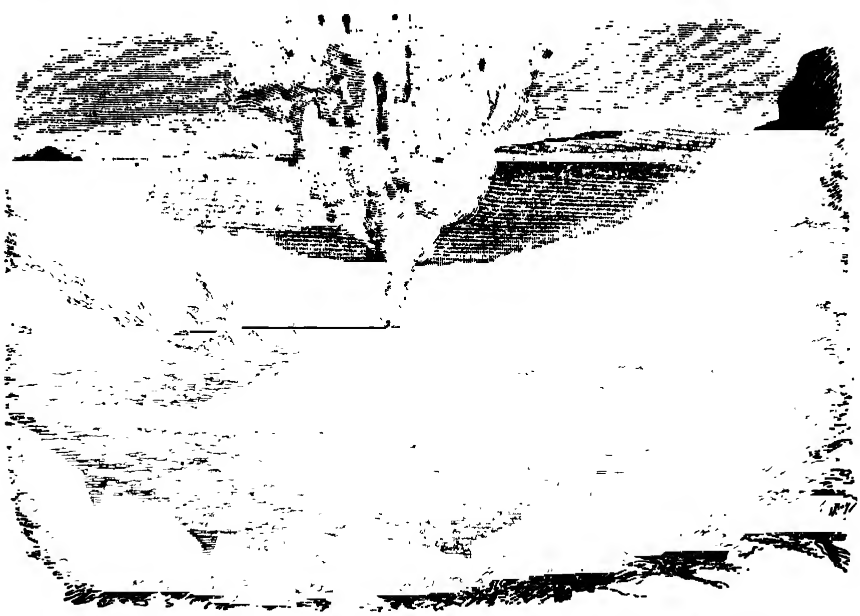


FIG. 78.—*The Crater of Vesuvius after the Eruption of* 1838; *with Ischia in the distance.*

cone in the wrecked crater, which it ultimately fills again, forming a new terminal peak. This process is well shown in the above sketch (Fig. 78), taken by Sir Henry W. Acland after the great eruption of 1838. The new cone gradually rose above the surrounding crater walls.

Some volcanoes, as for example Mauna Loa, which rises to the height of 13,760 feet, are built up almost entirely of lava-streams, whereas others, such as Vesuvius and Etna, consist largely of beds of ash and scoriæ. As the mountain grows in size, the great pressure of the lava in the central crater, coupled with the violence of the paroxysmal eruptions, rend and fracture the surrounding volcanic materials. Into these rents lava is injected, forming vertical dykes, of various dimensions, which traverse the mountain from its centre towards its circumference.

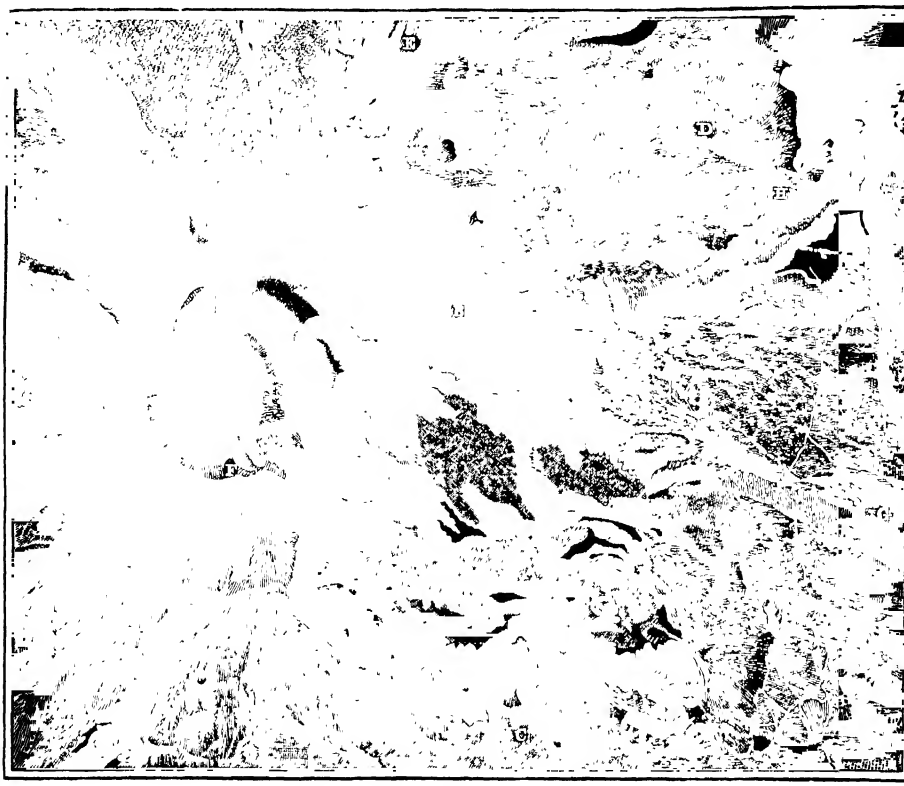


FIG. 79. *Plan of Etna* (reduced from an Italian map).

A. Val del Bove.
B. Monte Frumento.
C. Monte Monaco.
D. Monte Gresimo.
E. Monte Nevo.
F. Casa Inglese.
G. Cava Grande.
H. Serra Buffa.

The larger of these fractures also serve, when they radiate from the centre of eruption, as new channels of ejection and lava-flow, as in the instance of the eruption of Etna in 1865, when a rent opened which extended from Mount Frumento for a distance of $1\frac{1}{2}$ miles, in the course of which six cones from 300 to 350 feet high were formed; while, during the eruption of August, 1874, some great fissures were formed 3 miles in length, and

thirty-five secondary cones were thrown up. In this way Etna has become covered with several hundreds of these secondary cones, some of which are small mounds, while others form hills of considerable size (see Plan, Fig. 79).

FIG. 80. *Spiracles or 'Boccas' on Vesuvian Lava-current of* 1855. (From Scrope.)

Besides these cones of ejection, a number of miniature parasitic cones (?) are often formed on lava-streams by the discharge of steam and gases from

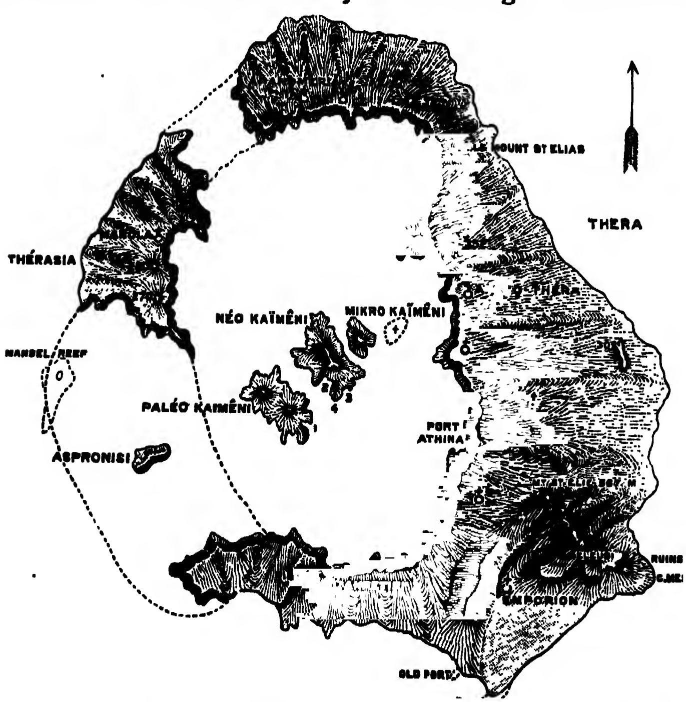


FIG. 81. *Map of Santorin*, 1838. (After Virlet.) *The dotted lines complete the round of the old crater.*

the cooling lava. They vary in their dimensions from a few feet to a few yards in height, and are common on most volcanoes (Fig. 80).

On the other hand, the violence of some explosions has been such as to blow away a great part of the mountain, and to replace the former smaller crater by a cavity of vast dimensions, the outer walls of which

remain encircling an area in which the subsequent eruptions have taken place, as for instance the heights of Somma in relation to Vesuvius; or, as an instance of one on a still larger scale, the islands of Thera and Therasia in relation to Santorin, where the exploded crater now forms an enclosed bay 4 by 7 miles across, and 600 feet deep, in the centre of which the modern volcano forms the small island of Néo Kaïmêni.

The following section is to show the relation of the modern to the old volcano, the last explosion of which possibly resembled that of Krakatoa.

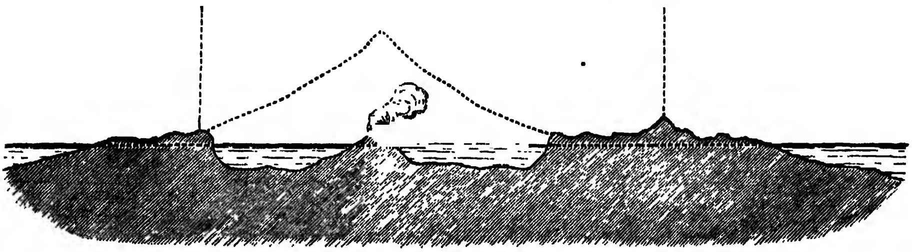


FIG. 82. *Section across Santorin, with the old volcano restored in outline.*

The volcano of Bourbon presents another instance of a central peak, encircled by the cliffs of an earlier crater formed after a great explosive eruption. The present peak is the result of a succession of small eruptions.

FIG. 83. *Volcano of Bourbon.* (Scrope.)

Sometimes round and deep cavities are formed by these explosive eruptions, which afterwards give rise to lakes, such as the beautiful crater-lakes of Avernus, Nemi, Albano, and others in the neighbourhood of Rome. A very interesting instance of an old crater-lake is also presented by Lac Pavin, surrounded by basaltic cliffs, Fig. 84; and by the Laacher See.

Character of Eruptions. The eruptions are very generally accompanied or preceded by earthquakes of a minor and local character. The first paroxysms of an eruption are of the greatest violence. They gradually decrease in force, and cease altogether after a few days or weeks, although they are sometimes prolonged over months or even years, when the mountain returns to a state of repose which lasts a variable interval,—now two or three years, and at other times two or three centuries or more,

Only a very few volcanoes, like Stromboli (Fig. 85), Kilauea, and probably some of the South American volcanoes, are in a state of constant activity.

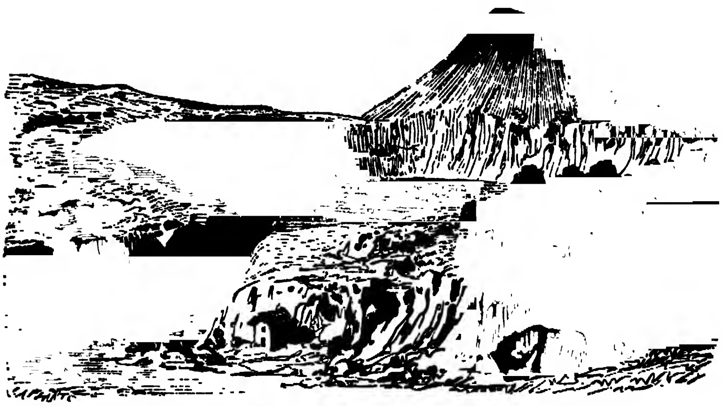


FIG. 84. *Lake Pavin and the Puy de Mont-Chalme in Auvergne.*

At times the eruptions are local and exceptional. A volcano breaks out in new ground, is active for a short time, and then relapses apparently into a state of permanent quietude. The volcano of Monte Nuovo near Naples is a well-known example of this (Figs. 86 and 87). In this case an eruption burst out in September, 1538, in unbroken ground, and threw up so large a quantity of mud, ashes, and scoriæ during two days, that a hill

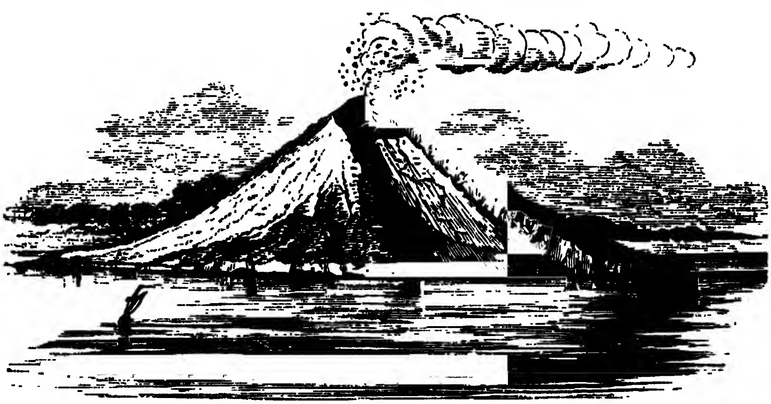


FIG. 85. *Stromboli from the North-west, April,* 1874. (Scrope.)

430 feet was built up in that short time. The eruption then ceased, nor has it been since renewed.

Lava-flow. The discharge of lava is extremely variable. That from the fissure at Frumento on Etna during the first six days of the eruption was estimated at ninety cubic metres a second. Sometimes the flow is slow, at other times rapid. Sometimes it ceases after a few days, at other times it is prolonged for months and even years. Sometimes the

flow of lava takes place on the flanks of the volcano and at low levels; at others, it issues from the central crater, at heights above the sea-level of about 4000 feet on Vesuvius, 11,000 feet on Etna, 15,000 feet on Teneriffe;

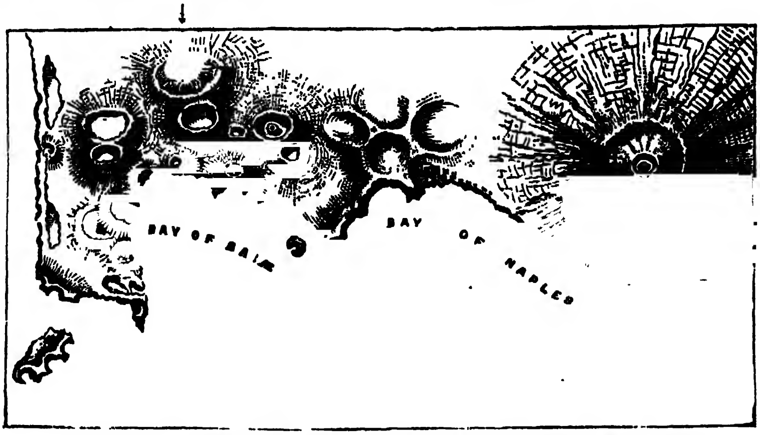


FIG. 86. *Plan of Vesuvius and the Volcanoes of the Phlegræan Fields.* (Scrope.)
The arrows point to Monte Nuovo.

while in some of the great peaks of the Andes, lava is vomited from craters open at a height of 19,000 feet or more above the sea-level.

The large outpours of lava in the island of Hawaii are so peculiar and so different from what they are elsewhere, that a special reference to the volcanoes of that island may be of interest. The crater of Mauna Loa is

FIG. 87. *Monte Nuovo.* (Scrope.)

a great pit 2 to 3 miles across, and generally about 700 to 1000 feet deep, situated on the summit of a flattened dome 13,370 feet above the sea-level. The lava, which is always seething in the crater, rises every few years to the brim and overflows; but its more usual mode of escape is by fissures or rents, 3000 to 5000 feet lower down the slopes of the mountain, through which it suddenly bursts under enormous pressure with a force that propels it upwards in gigantic jets—not spasmodically, but as from a steady flowing tap. After an eruption, the lava falls in the crater sometimes so deep as to be out of sight.

The crater of Kilauea is 16 miles distant from Mauna Loa, and nearly 10,000 feet lower. It forms another great pit, some 600 feet deep, and above 3 miles in its greatest diameter. In the centre of this is an inner

pit 400 feet deep, at the bottom of which the lava is in a state of constant movement. A large portion of its area is covered by a firm crust, but one portion, generally about 1000 feet across, forms an ever-boiling and fiery liquid lake, shifting its position and dimensions from time to time as it moves from one part to another of the partially consolidated surface. In this incandescent lake the lava boils up like springs in a pond, and with the fluidity of molten iron. Here and there on the surface, small cones of liquid lava arise, which rapidly increase in size and finish by throwing up a spray of the molten fluid to the height of 50 to 80 feet, when they fall back and subside, and new ones appear in other parts of the lake, thus keeping up a permanent state of activity. At intervals of a few years,

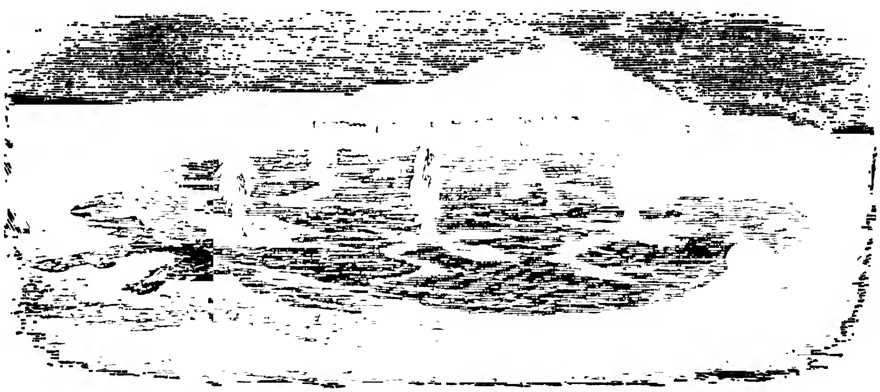


FIG. 88. *The Lake of Molten Lava in the Crater of Kilauea.*

the lava fills the whole of the vast crater and occasionally overflows; but more usually, as in the case of Mauna Loa, it makes its escape lower down the sides of the mountain through rents which tap the main duct (Fig. 89).

I am indebted to Mr. Frederic Bonney, who visited the volcano in September 1881, for photographs and drawings of this remarkable scene, from which the above sketch (Fig. 88) is reduced.

A somewhat analogous discharge of vapour occurred during an eruption in 1875 between Barfell and Jokulsa in Iceland. The lava was there thrown up in columns (of which there were some 20 to 30) to a height of from 200 to 300 feet. It then spread and fell in small particles. A bluish steam rose to a great height in the air, despite a heavy wind, expanding and whitening as it ascended [1].

Where the volcano is above the snow-line, its eruption sometimes causes serious inundations. When the supposed extinct volcano of Corpuna in Peru burst into eruption in 1878, the snow which had crowned the summit from time immemorial suddenly melted. Torrents of water rushed down the side of the mountain, washing with it immense quantities of

[1] 'Nature,' vol. xii. p. 75.

earth and stones, blocking the river below, and causing it to flood the adjacent country[1].

Volcanoes in adjacent districts are rarely affected at the same time. The eruptions of Vesuvius are generally independent of those of Etna. Still at other times they act in sympathy. In 1865 Vesuvius and Etna vomited lava at the same time, and Stromboli was slightly affected. During four of the great eruptions of Mauna Loa, the crater of which is 13,370 feet high, the crater of Kilauea, only a few miles distant and 4000 feet high, was not affected.

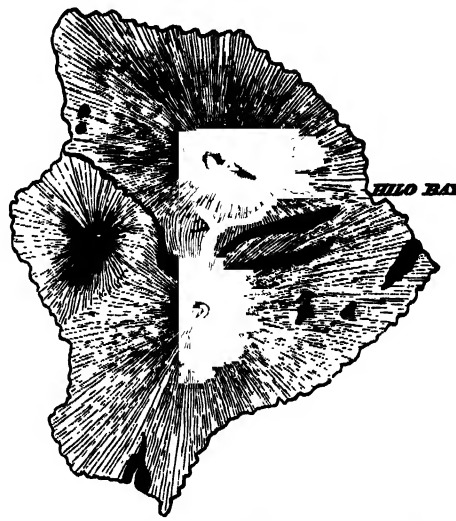


FIG. 89. *Map of Hawaii in the Sandwich Islands.* (Dana.) – *L* Mauna Loa. *K* Mount Kea. *H* Mount Hualalai. *P* Kilauea. 1. Lava-flow of the eruption of 1843. 2. Eruption of 1852. 3. Eruption of 1855. 4. Eruption of 1859. *m* First appearance of eruption of 1868. The island is about 90 miles long by 70 wide.

It is beside our purpose to give any account of those great eruptions which from time to time have spread devastation over the surrounding country. It will merely be necessary to direct attention to those points which bear on the constitution of volcanoes, and their relation to underground conditions of temperature and water-percolation.

Position. Volcanoes are mostly situated on the borders of continents, and in islands. They are especially numerous on the shores and islands of the Pacific; less numerous in the Atlantic and Indian oceans; while a smaller number exists in the Mediterranean and Red-Sea areas. They are not confined to any region of the globe, for they are met with in the tropics, in Iceland, in the Aleutian Islands, and amidst the perpetual snow and ice of the Antarctic continent. None, however, have been found at present in action in the interior of the American continent, or of Africa, Europe, or Australia; but one or two are said to exist in Central Asia (see Map, No. II, p. 216).

Height. Volcanoes range in height from 300 or 500 feet to mountains many thousand feet in height. Vesuvius varies from a little under to a little over 4000 feet; Etna is about 11,000 feet; while Cotopaxi in Peru (Fig. 90) rises to the height of 18,876 feet, and Acongagua in Chili is said to be 23,000 feet high, but these latter stand on high plateaux or ranges of sedimentary and crystalline rocks, rising 9000 to 10,000 feet above the sea-level.

[1] 'Nature,' vol. xvii. p. 423.

Number. The number of volcanoes in the world may be estimated to amount to about 500, of which more than 300 are active. Dana enumerates 207 in the Pacific and Indian Ocean areas alone. The extinct forms are of late geological date, but dormant within historical times.

Size of Lava-Streams. It will be sufficient to give the dimensions of a few of the more important recent lava-streams, to serve as points of comparison with the eruptions of geological times. Among the greater

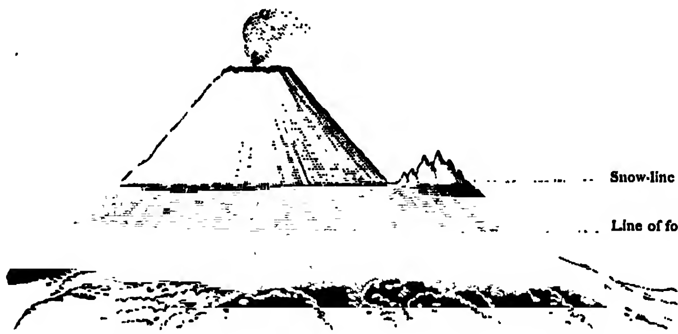


FIG. 90. *Cotopaxi in Equador, seen from a distance of 90 miles.* (From Scrope.)

flows from Etna, is the one which destroyed Catania in 1669. It is fourteen miles long, and in some parts six miles wide; but another stream, belonging to some older eruption on the northern side of Etna, has a length of forty miles.

In 1783 a lava-torrent burst from the Skapta-Jokul in Iceland, and continued flowing for two years. It filled up the rocky beds of rivers, in many places 400 to 600 feet deep, and some 200 feet wide, flowing up their channels as well as down, filling deep lakes and an abyss of 600 feet below a water-fall, and spreading out over wide alluvial plains, in broad, burning lakes from 12 to 15 miles wide, and 100 feet in depth. The two principal streams were respectively 40 and 50 miles in length, and 7 and 12 to 15 miles wide, forming a mass said to surpass Mont Blanc in volume.

In the island of Hawaii, in 1840, a burning deluge of lava broke out 10 miles below the crater of Kilauea. It spread from 1 to 4 miles wide, and reached the sea, at a distance of 30 miles, in three days, and for fourteen days it plunged, in a vast fiery cataract a mile wide, over a precipice 50 feet high. In 1843 a similar stream flowed from the summit of Mauna Loa; and in August, 1855, the lava broke out at a spot 2000 feet below the summit, on the opposite side to Kilauea, and continued to flow during ten months, overwhelming an area of 200,000 acres. This stream was 60 miles long, from 1 to 10 miles wide, and from 10 to 300 feet in depth.

The areas covered by the products of modern volcanoes are very variable. In Vesuvius it is limited to less than 50 square miles. In Etna it does not exceed 2000 square miles. That of Hawaii is larger, or about 4040

square miles; and the greatest of existing volcanic areas, that of Iceland, may be estimated at the outside at about 20,000 to 25,000 square miles.

Composition of Lava. Lava consists of molten masses of mineral matter, which, cooling at the surface under the ordinary pressure of the atmosphere, assume, as they solidify more or less rapidly, a strong or a glassy structure—cellular externally owing to the escape of steam and gases. Molten lava flows with nearly the liquidity of melted iron or glass. It conducts heat very slowly, so that it forms a solid and very rough crust outside, while the molten stream still continues to flow underneath. Some lavas, where the liquidity is very great and the cooling rapid, form the dark vitreous glass-like substance called obsidian. At the volcano of Kilauea the liquidity is so complete, that the small jets of lava thrown up in the boiling crater by the escape of vapours, when acted upon by a strong wind, are blown out into fine threads like spun glass, which are called Pélé's hair.

The temperature of molten lava has not been determined with any degree of certainty. It melts silver and copper, the fusing point of the latter being 2590°F. It no doubt varies with variations of composition, and is generally supposed to be from 2500° to 3000°F.

Lavas consist of felspathic and augitic minerals, composed essentially of silicates of alumina and iron with variable proportions of magnesia, lime, potash, and soda (*ante*, p. 37). When felspathic bases predominate, the lava is generally of a light colour, and of low specific gravity, from 2·4 to 2·8. Where, on the contrary, augitic bases are in larger proportion, the colour varies from dark-grey to black, and the specific gravity ranges from 2·9 to 3. The former, in which silica enters in the proportion of from about 60 to 75 per cent., constitute the *trachytes*, *andesites*, *rhyolites*, *obsidians*, *pitchstones*, etc. The latter, which contain a smaller quantity of silica, varying from about 45 to 55 per cent., constitute the various *dolerites*, *basalts*, etc.

These are the extremes of the series; there are many intermediate varieties connecting the two. The Leucite-lava, or Amphigenite of Vesuvius, is one of the varieties of lava.

Incidental Minerals. All the varieties may contain, as incidental ingredients, either forming crystals imbedded in the lava or else coating cavities in it, a number of special minerals. Some of these, such as augite, leucite, titaniferous iron-oxide, etc., are due to crystallisation from the original magma; others, such as oligist-iron, sulphur, the metallic and alkaline chlorides, etc., to sublimation in the molten lava; whilst some, such as opals, chalcedony, and the large group of the zeolites, are formed by subsequent percolation and action of water during and after the cooling of the lava.

Volcanic Vapours. Volcanic eruptions are accompanied by the escape of an enormous mass of elastic fluids, consisting principally of the vapour of water, which, condensed by the cool atmosphere with which it

comes in contact, forms dense masses of white and heavy clouds that hang above the volcano, and fall in torrents of rain upon its flanks and over the surrounding country (Fig. 91). This is a very persistent feature in volcanoes; and in permanently active volcanoes, such as Stromboli, this vapour of water forms a constant cloud suspended over the peak when the air is calm. On Mount Erebus, in the Antarctic continent, the vapour issuing from the crater is at once converted into snow, which falls to the leeward of the volcano.

FIG. 91. *Eruption of Mount Vesuvius, October 1822.* (From a Neapolitan drawing.)

The vapour of water constitutes by far the largest part of the elastic fluids given off during eruptions—probably $\frac{950}{1000}$ or even $\frac{999}{1000}$ of the whole. M. Fouqué estimated that the quantity of vapour projected from Etna in the eruption of 1865 amounted to the large quantity of 22,000 cubic metres, or about five million gallons, daily.

After the lava has ceased to flow, heated gases and vapour continue to be discharged from holes or fissures in the lava-stream. These *fumarôles*, as they are called, vary in their nature with their distance from the crater; but in an order not always uniform. Generally the first are dry fumaroles, with anhydrous alkaline chlorides and small quantities of sulphurous acid and sulphates. Secondly, hydrochloric acid and sulphuretted

hydrogen, with small quantities of the vapour of water. Thirdly, vapour of water with a small quantity of sulphuretted hydrogen, or of sulphur, and sometimes hydrochlorate of ammonia; and, fourthly, vapour of water only [1].

It was long a question whether volcanic eruptions were ever accompanied by flames. The researches of M. Fouqué have now settled that point in the affirmative, for he has clearly determined the presence of hydrogen in the eruptions of Santorin, Etna, and Vesuvius. The disengagement, however, of this gas is very variable. It is generally small, though in a fissure at Torre del Greco, prolonged 330 feet from the shore, powerful jets of gas boiled up in the sea, and these consisted of 75 per cent. of free hydrogen, mixed with 25 per cent. of carburetted hydrogen, but this might have been due to the direct decomposition of the sea-water with some organic matter. Carbonic acid is rarely present.

Ashes. The solid ejectamenta consist of the lighter and more scoriaceous portions of the lava, and form what are called volcanic cinders and ashes (*lapilli*), together with volcanic dust derived from the violent trituration of the materials, portions of which repeatedly fall back into the crater, so that at the close of an eruption the ejections have often been reduced to clouds of dust and ashes. They are projected vertically by and with the elastic fluids and vapours to very great heights (see Fig. 91). It has been estimated that the column thus formed sometimes attains a height of 8000 to 10,000 feet [2].

When portions of the lava are thrown up in a liquid state, and fall outside the crater in small fragments, which harden rapidly as they fall, they assume a long globular or pear-shaped form, porous or hollow in the centre (or sometimes enclosing rock fragments), known as *volcanic bombs*. When again lavas have been thoroughly permeated and rendered frothy by the escaping gases or vapours, they assume on cooling a light spongy texture,—often forming the material known as pumice.

The earliest known and most familiar instance of quantities of ashes projected from a crater during eruption is that by which Pompeii was entombed, when also the shower of ashes was accompanied by torrents of rain due to the condensed vapours. There are instances where the volcanic dust has been carried by high winds to great distances. In February 1600 the volcano of Guaytaputina, in Peru, threw out during twenty continuous days a quantity of stones, scoriæ, and ashes that covered the surrounding country to a distance of 90 miles on one side and 120 miles on the other and to a

[1] The student should refer to the various papers of M. Chas. St. Clair Deville in the Bull. Soc. Géol. de France, and to the works of M. Fouqué for information on this subject.

[2] The more recent observations of Whymper assign to the column of 'inky black smoke,' which rose with immense rapidity during an eruption of Cotopaxi in 1879, a height of about 20,000 feet, or of 40,000 feet above the sea-level; and it is said that the steam cloud from Krakatoa in 1883 must have reached a height of 36,000 feet, if it did not at one time exceed 60,000 feet (Prof. Bonney in 'Proc. Roy. Soc.' June 1884).

depth of many feet. Another remarkable case is that reported of the eruption of Coseguina in Central America in 1835, when, it is said, volcanic dust was carried to Chiapa (Mexico), a distance of 400 leagues; and Captain Eden reported that, when in lat. 7·26° N. and long. 104·45° W., 900 miles distant from the nearest land and 1100 from this volcano, his ship ran for 40 miles through floating pumice, some pieces of which were of considerable size.

Lava-streams occasionally flow into the sea; and showers of volcanic ashes are often carried by the wind far from land and then fall into the sea, where, after drifting for a time with the currents, they sink and mix with the marine sediments [1]. In one of the eruptions of Kilauea the lava flowed into the sea with loud detonations. Mr. Coan states that the molten mass was immediately shivered like glass into millions of particles, which were thrown up in clouds that darkened the sky; and the ocean waters were so much heated that the shores for twenty miles were strewed with dead fish [2]. The exploded lava formed cinder-heaps, which, drifted about by the tides and currents, became laminated like the alluvium of a river.

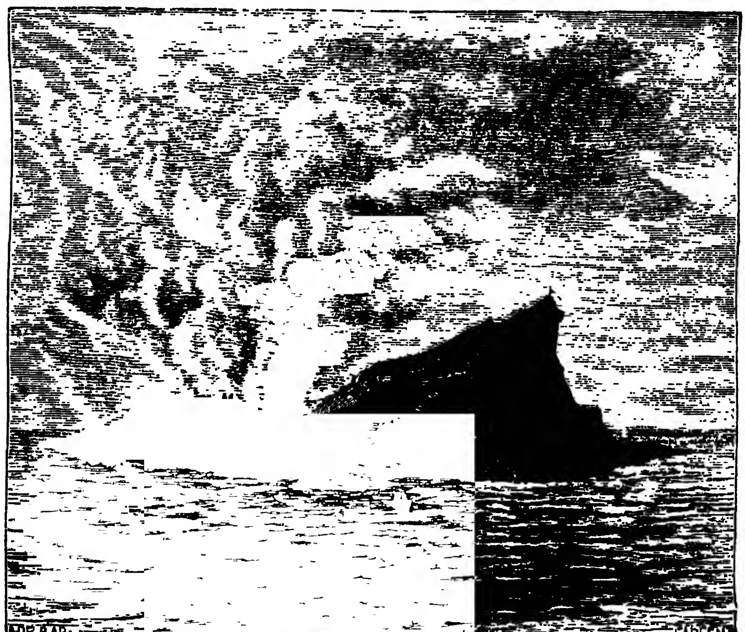


FIG. 92. *Graham's Island.* (After Constant Prévost.)

Submarine Eruptions. Volcanic eruptions also take place under the sea. A well-known instance is that of Graham's Island or Île Julie, which, in 1831, was thrown up during a volcanic eruption in the Mediter-

[1] The 'Challenger' Expedition affords frequent evidence of this fact (*ante*, pp. 124, 130).
[2] Dana, 'U. S. Exploring Expedition,' vol. x. pp. 189–193.

ranean, between Sicily and Pantellaria, at a spot where there had previously been a depth of above 100 fathoms of water. It attained a height of about 200 feet above water, and consisted solely of loose cinders, scoriæ, some blocks of lava, with a few calcareous rock fragments. It was washed away in the course of a few months, leaving a submarine bank, 12 miles wide, with a depth of water of 18 fathoms. At its edge the depth increases to 100, and then to 200 and 500 fathoms.

In another instance, however, a volcanic island, thrown up in the sea amongst the Aleutian group in 1796, and which at the time attained a height of 250 feet, was found by Kotzebue, who visited it again twenty years afterwards, to have increased to a height of 3000 feet with a circumference of about 20 miles.

Submarine eruptions at great depths have also been frequently suspected both in the Pacific and in the Atlantic from the violent agitation of the sea in the absence of wind, by muffled sounds from beneath, by shocks to vessels as if struck on a bank or rock, and by the scoriæ or pumice floating on the sea around. These symptoms are occasionally accompanied by columns of ashes and steam: and the water is sometimes so heated and polluted by deleterious gases that large numbers of fish are killed. During one submarine eruption between Tonga and Hapai a column of water was shot up to the height of 100 feet.

These eruptions, and those of volcanoes near coasts, often give rise to immense floes of pumice, which cover the adjacent seas and are carried to great distances by currents. After the eruption of Coseguina a bank of this sort was met with at a distance of several hundred miles from land; and after the recent great eruption of Krakatoa the adjacent sea was blocked by a sheet of pumice fragments many feet thick and extending over several hundreds of square miles.

Destructive sea waves are also a common accompaniment of such eruptions. The eruption of Noumea in the Isle of Tanna (New Hebrides) was accompanied by a sea wave 50 feet high, which swept over and destroyed the native plantations. Outside the harbour, three rocks rose in water of 11 fathoms depth.

It is probable that Etna first commenced as a submarine volcano, for the lower volcanic rocks alternate with beds containing marine shells, and the area all around is one evidently of recent geological (Pliocene and Pleistocene) elevation. Santorin was also at first a submarine volcano dating back to Pliocene times. Vesuvius, and possibly Hecla, commenced in the same manner. Many other instances might be cited.

Effects of Heat. With regard to the effect produced by the heat of the lava-streams on the rocks with which they come in contact, it is generally less than might be supposed. Where the lava in Auvergne has passed over granites and limestones there is little change; the limestones

have been rendered slightly more crystalline, but the alteration is very superficial.. The lavas of Vesuvius and Etna in passing over argillaceous soils or beds have baked them into a red jasper-like substance, but merely to a depth of a few inches, or at most of two or three feet. Sandstones are rendered harder by the same cause, and are sometimes partially bleached. The reader will find instances of the effects produced by contact with other igneous rocks in Chapter XXII.

Secondary Minerals. Blocks of Subapennine limestone and other rocks thrown out of the crater of Vesuvius, where they have been exposed to a stronger and more maintained heat, exhibit, however, much greater change. The earthy limestone is converted into a white crystalline rock; and in these and other blocks a large number of minerals, amongst which the following are the most common, have been formed by metamorphic action[1]:—

Idocrase	Zircon	Sphene
Chrysolite	Augite	Topaz
Garnet	Hornblende	Biotite
Thomsonite	Potash-mica	Lapis-lazuli
Sodalite	Nepheline	Wollastonite
Scapolite	Humboldtilite	Sarcolite.

These blocks are chiefly confined to the earlier eruptions of Vesuvius, and are most common amongst the old lavas of Somma.

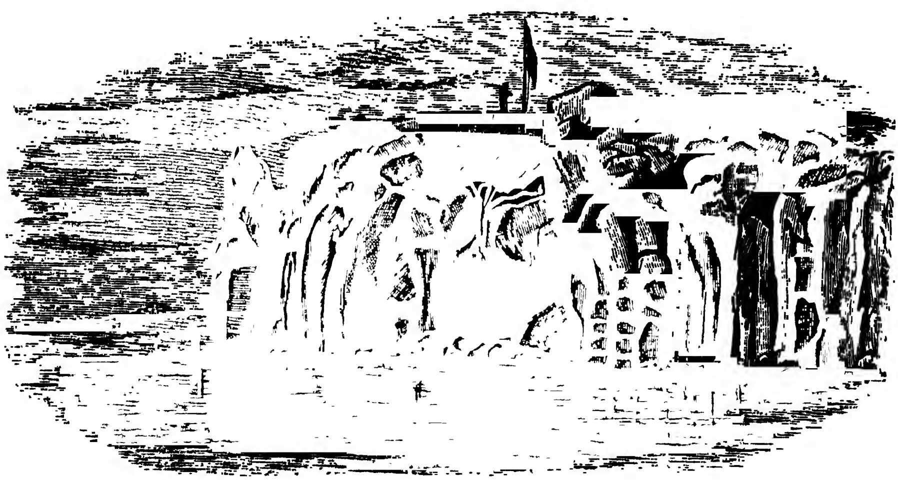


FIG. 93. *Lava-stream of 1794, where it advanced into the sea at Torre del Greco.* (From a sketch in 1834, Dr. Buckland's collection.)

Columnar Structure. When the lava-stream is of great thickness, and the cooling is prolonged, the lava sometimes assumes the columnar structure so common in older eruptions and in basalts.

This structure has been attributed to a tendency of the cooling mass to

[1] See Phillips' 'Vesuvius,' pp. 266–301, for a full account of these minerals.

segregate into nodules, which as they increase in size press one against another, and are thus forced into the jointed prismatic structure forming the remarkable natural colonnades of volcanic and basaltic districts. The columns are polygonal, the number of sides being very variable and fitting close together. There is, however, a difficulty in supposing how the spheroids could have so arranged themselves as to fit exactly the one over the other; and Mallet asserted that the compression would not produce prisms at all, but would squeeze the spheroids in rhombic dodecahedrons [1]. Mr. Mallet, Prof. J. Thomson [2] and others, contend that the prismatic structure is due to slow and gradual cooling, which by inducing contraction causes the rock to split (as when starch dries) into prisms having a columnar structure and formed at right angles to the cooling surfaces. This explanation does not, however, satisfactorily account for the jointed structure, and especially for the cup-and-ball articulations (see p. 281). Traces of prismatic structure occur in some of the lavas of Vesuvius (Fig. 93), and in other recent lavas.

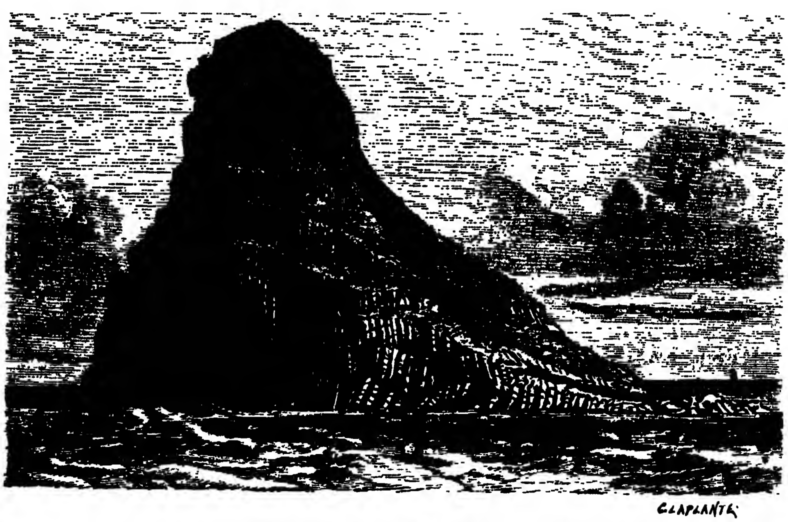


FIG. 94. *View of the Isle of Cyclops, off the Sicilian Coast.*

The columnar structure is especially common amongst the old lava-streams of Auvergne, and in those of the earlier eruptions of Etna. A well-known and fine instance is that of the Isle of Cyclops on the coast of Sicily, which consists of a pile of such columns about 200 feet high, left isolated and separated from the mainland by long-continued denudation.

[1] 'Phil. Mag.' for Aug. and Sept., 1875.
[2] 'Brit. Assoc. Report' for 1863, p. 89.

It is not necessary to multiply examples, as they abound in all old volcanic districts. The prismatic structure sometimes extends also, but generally in a less perfect degree, to trachytic and other rocks of the acidic group.

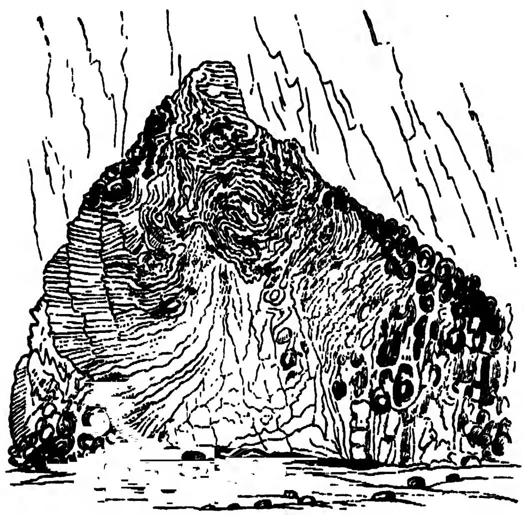


FIG. 95. *Prismatic and globiform Pitchstone, Isle of Ponza.* (Scrope.)

This structure is often connected with a globiform structure which becomes apparent with the decomposition of the rock. This is well seen in the following section given by Scrope, where prisms of a green vitreous pitchstone separate into perfect spheroidal or ovoidal masses, from a few inches to a foot in diameter, which break up into concentric laminæ like the coats of an onion. In some places the pillars consist of piles of such balls, as in the Cheese-grotto at Bertrich-Baden in the Eifel.

Cause of Volcanic Action. Volcanoes are commonly considered by geologists to be connected with an independent and central source of heat beneath the crust of the earth, and the volcano to be an opening through which the lava is propelled outwards, either by occluded vapours and gases in the original magma, or else by the pressure due to contraction arising from the secular cooling of the globe. Another theory is that the metals of the earths and alkalies exist in an unoxidised state in the earth, and that, when water gains access to them, the evolution of heat arising from its decomposition is so great that the rocks are fused and ejected by the gases and steam generated thereby. A third theory, more recently propounded by the late Mr. Mallet[1], is that, owing to the cooling of the earth and consequent contraction of the crust, the pressure along lines of fracture becomes intense; and that the crushing caused by the pressure is, on the doctrine of the convertibility of forces, converted into heat; and he gives some very elaborate calculations to prove that the pressure is sufficient to produce these results.

There are many objections to Mr. Mallet's theory, such as, amongst others, the general uniformity of lava all over the world, and the absence of volcanoes in so many mountain-chains where the pressure and disturbances have been the greatest; but every geologist will do well to study his

[1] 'On Volcanic Energy,' Phil. Trans. for 1873, p. 147.

interesting memoir for the investigations which it contains on the effects of pressure and heat, and other physical questions.

The chemical theory, as it is termed, now finds few supporters amongst geologists, although it has had amongst its advocates Sir Humphry Davy and Dr. Daubeny. It was, however, subsequently abandoned by Davy.

The Presence of Water. The enormous discharge of vapour and gases during volcanic eruptions shows how great a part water plays in the phenomena, and geologists generally consider that, in some way or other, the explosive power of steam is not only the main agent of disturbance in the ejection of the ashes and cinders, but, according to many eminent vulcanologists, is the sole and primary cause of the extrusion of the lava likewise. On this last point, however, there is a difference of opinion. While admitting the presence of water, and attributing to its presence the violent explosive action, it may be questioned whether the flow of the lava is not due to the operation of other causes, and that the rest are secondary effects dependent on some other primary cause.

The Vapour of Water the supposed Cause of Eruption. The late Mr. Poulett-Scrope considered that it was proved beyond dispute, by the evidence of the phenomena described above, that the rise of lava in a volcanic vent is occasioned by the expansion of volumes of high-pressure steam, generated in the interior of a mass of liquefied and heated mineral matter within or beneath the eruptive orifice. He further remarks that the great bubbles of vapour that burst from the lava as it rises in the crater, in explosions which form the chief feature of every volcanic eruption, evidently ascend by the force of their differential specific gravity from a certain depth within the boiling mass. At what depth these volumes of vapour are generated is left a question, although it is evident that it is intended to be somewhere in the volcanic foci. It seems reasonable to suppose that, if any amount of vapour is generated at considerable depths beneath an active volcanic vent, it only reaches the external surface in a state of extreme condensation, and entangled in the liquid lava which rises with it and escapes outwardly, just as any other thick or viscid matter exposed to heat from beneath, in a narrow-mouthed vessel, ***boils up*** and ***over*** the lips of that aperture [1].

Sir Charles Lyell supposed that large subterranean cavities exist at the depth of some miles below the surface in which melted lava accumulates, and that when water penetrates into these the steam thus generated may press on the lava and force it up the duct of a volcano in the same manner as a column of water was supposed to be driven up the pipe of a geyser [2].

[1] 'Volcanoes,' 2nd ed., p. 40.
[2] 'Principles of Geology,' 10th ed., vol. ii. p. 221.

Professor Judd also considers that volcanic outbursts are due to the accumulation of steam at volcanic centres; that the tension of the imprisoned gas eventually overcomes the repressing forces, and that in the expansive force of such great masses of imprisoned vapour we have a competent cause for the production of the fissures through which volcanic outbursts take place [1].

On this hypothesis it is assumed that the vapour and gases to which the extrusion of lava is due exist imprisoned, as it were, in the volcanic foci, and that it is their effort to escape that forces up the lava in the volcano. This necessarily assumes that water must be present in the fused mass at its greatest depths, otherwise the trajectile force and impulse implied by the expulsion of the lava would be wanting in its initial stage. The presence of the water at the base of action would in short be as imperative as that, in a gun, the explosive must be in the breech.

Objections. Among the objections that present themselves to this hypothesis are,—(1) if the molten mass were so permeated by gases and vapours, the eruption of lava and the discharge of vapours would always be concurrent, and there could be no discharge of the one without the accompaniment of the other; whereas there are many eruptions which are altogether explosive, while in other eruptions—many of them very large—the flow of lava is effected quietly and without the detonations and ejections caused by the explosion of vapour. (2) Another objection is that all lavas would be more uniformly scoriaceous, and that vapour-bubbles would show themselves more generally; but there are lavas which are perfectly compact, although they have outflowed under the usual atmospheric pressure. (3) Again, it is difficult to conceive how these vapours and gases could have become incorporated with the molten magma, unless we admit with Dr. Sterry Hunt that, between the solid crust and the solid nucleus of the earth, there is a layer consisting of the outer part of the originally congealed primitive mass, disintegrated and modified by chemical and mechanical agencies and impregnated with water, now in a state of igneo-aqueous fusion [2]; or with Mr. Osmond Fisher, who connects volcanic eruptions with the extravasation of a primogenial water-substance in the molten magma [3]. Otherwise, that water should find its way down to the volcanic foci *through* the crust of the earth is highly improbable, as a point must be reached where, there is reason to suppose, the tension of the vapour will equal the hydrostatic pressure of the descending water and stay its course. Further, if such were not the case, not only the volcanic, but likewise the plutonic, rocks would have been subject to ejection under the same conditions and with similar subaerial results.

[1] 'Volcanoes,' pp. 33 and 189.
[2] 'Chemical and Geological Essays,' p. 61, *et sequitur*.
[3] 'Physics of the Earth's Crust,' pp. 96 and 284.

Another hypothesis, which also assumes water to be the prime motor of eruption, but considers its introduction to the volcanic foci to be coincident with the eruption itself, supposes fissures to be formed in the bed of the sea, by which a direct passage is opened for the sea-water. The objections to this hypothesis are, that it is not possible to suppose a fissure down which water could have passed without its forming a passage for the escape of the lava itself; nor can we conceive the steam, if so produced, could have had the force to eject a column of lava of the great height required to reach from the volcanic foci to the summit of the volcano, or that it would take the longer, more resisting, and more indirect channel, in presence of the open and unobstructed fissure.

Fresh and Salt Water. At the same time it is evident that water plays a very important part in volcanic eruptions, and also that sea-water does gain access to the volcano; but, although the presence of chlorides and of hydrochloric acid points to the presence of salt-water, other circumstances equally indicate the agency of fresh water.

Humboldt has noticed, with respect to some of the volcanoes of South America, that vegetable remains were present in the mud and water ejected: and, in other cases, fishes such as live in the obscurity of cavern waters of the disturbed district.

Ehrenberg found in some of the volcanic rocks of the Rhine *fresh-water* 'infusorial' (Diatomaceous) remains. He states also that in the Island of Ascension there exists a considerable deposit of volcanic ash, which is clearly shown to be made up exclusively of microscopic organisms, including the remains of siliceous Diatomaceæ; and these are not species inhabiting the sea, but are without exception species confined to fresh water. At the same time he mentions that there is a volcanic tuff forming mountain-masses in Patagonia which consists largely of marine Diatomaceæ. It has also long been ascertained that, not only are almost all the elements of sea-water found in the gases and deposits of fumaroles, with the exception of the salts of magnesia which has become fixed in the lava, but sea-salt itself is often found in lava or is deposited on its surface. The lava of Frumento contained a notable quantity. There is therefore reason to suppose that the water, which gives rise to the vast discharge of vapour in volcanic eruptions, must be derived from other sources than water occluded in the original molten magma. For these other sources, I look, as some other geologists, Dana[1] especially, have contended, to land-surface waters in the first place, and to sea-water in the second; but in neither case do I consider that those waters are the primary cause of the volcanic eruption.

The Rainfall. Rain, falling on such materials as volcanic ashes,

[1] See 'United States Exploring Expedition,' 1838-42, vol. x. p. 366; and his 'Manual of Geology,' 1875, p. 711.

tuffs and lava, is quickly lost or absorbed. All observers have remarked on the persistent absence of streams and springs on and immediately around volcanic cones, although their flanks are often deeply scored by the temporary torrents caused by heavy rains. Part of this water, passing through fissures of the lava or the loose beds of ashes, finds its way into the volcanic vent or shaft. If no eruption be going on, the permanent presence of water from this source is nevertheless indicated by the constant small cloud of aqueous vapour which forms over many volcanoes even during periods of rest.

But while a certain portion of the surface-waters trickles through the heated sides of the shaft, and is there converted into steam, the larger portion accumulates underground amongst the cavities and fissures of the volcanic materials, and it is in some such subterranean reservoirs that the Diatomaceæ, vegetation and fishes, before referred to, live.

Underground Waters. Another and deeper source of water-supply exists in the permeable sedimentary strata on which the volcano may rest and through which its shaft must pass. As before explained, all porous strata, when below a certain level,—such as that of the adjacent river-valleys or of the sea,—are permanently saturated with this underground water; and, if the water be drawn off at any one point, an influx from all the circumjacent parts will take place and continue until the original level is restored.

When the volcano is in a state of repose these hydrostatic conditions are maintained with the same regularity and permanence as in any non-volcanic district. The water accumulates up to its normal level in the adjacent strata; and, if the column of lava in the shaft stands below that line of water-level, the water, on the cooling and consolidation of the surface of the lava after the eruption is over, will accumulate there as it would in an ordinary well.

Exhaustion of the Underground Water. In fact, when left for a time undisturbed, the underground fissures and cavities of the detrital volcanic materials forming a volcano must soon become filled by the infiltration of rain-water from the surface; while any permeable strata on which they rest must also get charged with water from a distance according to the known laws regulating underground waters. No eruption of lava can then take place without causing disturbance in these underground waters. The first to be affected will be the water in the crater and in the cavities of the volcanic mountain. As the pressure of the ascending column of lava (I am assuming for the moment an independent force for its ascension) splits the chilled crust of lava formed in the vent subsequently to the preceding eruption, the surrounding water finds its way to the heated rock below, and leads to explosions more or less violent. Further, as the fluid lava breaks more completely through the crust, and the mountain becomes

fissured by the shocks and by the pressure of the ascending column of lava, all the water stored in the mountain successively flows in upon the hot lava and flashes off into steam. Thence those more violent detonations and explosions—those deluges of rain arising from the condensed steam with which so many great eruptions commonly commence. As the more superficial waters lodged in the superincumbent lava-beds and ashes are exhausted, the springs in the deeper underlying sedimentary strata, cut through by the fissures along which the volcanic duct passes, come into play, and discharge their contents more or less rapidly into the duct, where, either at once or after a short interval, it flashes into steam and rises in vast bubbles of vapour to the surface of the lava.

Of the quantity of this underground water some notion may be formed by the fact that the deepest of the three springs in the Tertiary strata underlying the mass of volcanic materials on which Naples stands discharged, when first tapped by an artesian boring, two cubic mètres (440 gallons) per minute. During the eruption of a volcano the powerful shocks and vibrations must shatter the strata and detach masses of rock from the sides of the main duct, so that the water lodged in the strata would be liberated spasmodically and pass into the molten lava in successive increments; or it may pass in by capillarity, for it is well known that this property exercises a remarkable influence on the conditions of equilibrium of fluids when placed on two sides of a porous body. M. Daubrée has shown that water will thus pass through sandstone against a pressure of steam much greater than that of the opposing column of water. The experiments were only carried to the extent of a steam pressure of two atmospheres; but it was evident that the limits of the power were not reached. They further also showed that heat increased the transmitting power[1]. There is reason, therefore, to suppose that water, under the great hydrostatic pressure that exists at depths beneath volcanic mountains and assisted by capillarity, may flow freely into the volcanic ducts, especially when aided by the intermittent relief of pressure afforded by the rise and fall, or pulsations, of the column of lava.

Gunpowder evolves by its combustion an amount of gases which occupies from 500 to 1000 times and upwards the volume of the original body. Water, on the other hand, in passing into steam expands to 1700 times its volume. Every one will be familiar with the force of steam in the cases of boiler and similar explosions. Among the many disastrous instances recorded may be mentioned one that happened during the eruption of 1843, when a lava-stream flowed over a mere cistern of water in a village on the flanks of Etna, and the explosion which ensued was nevertheless of so destructive a character that 69 persons lost their lives.

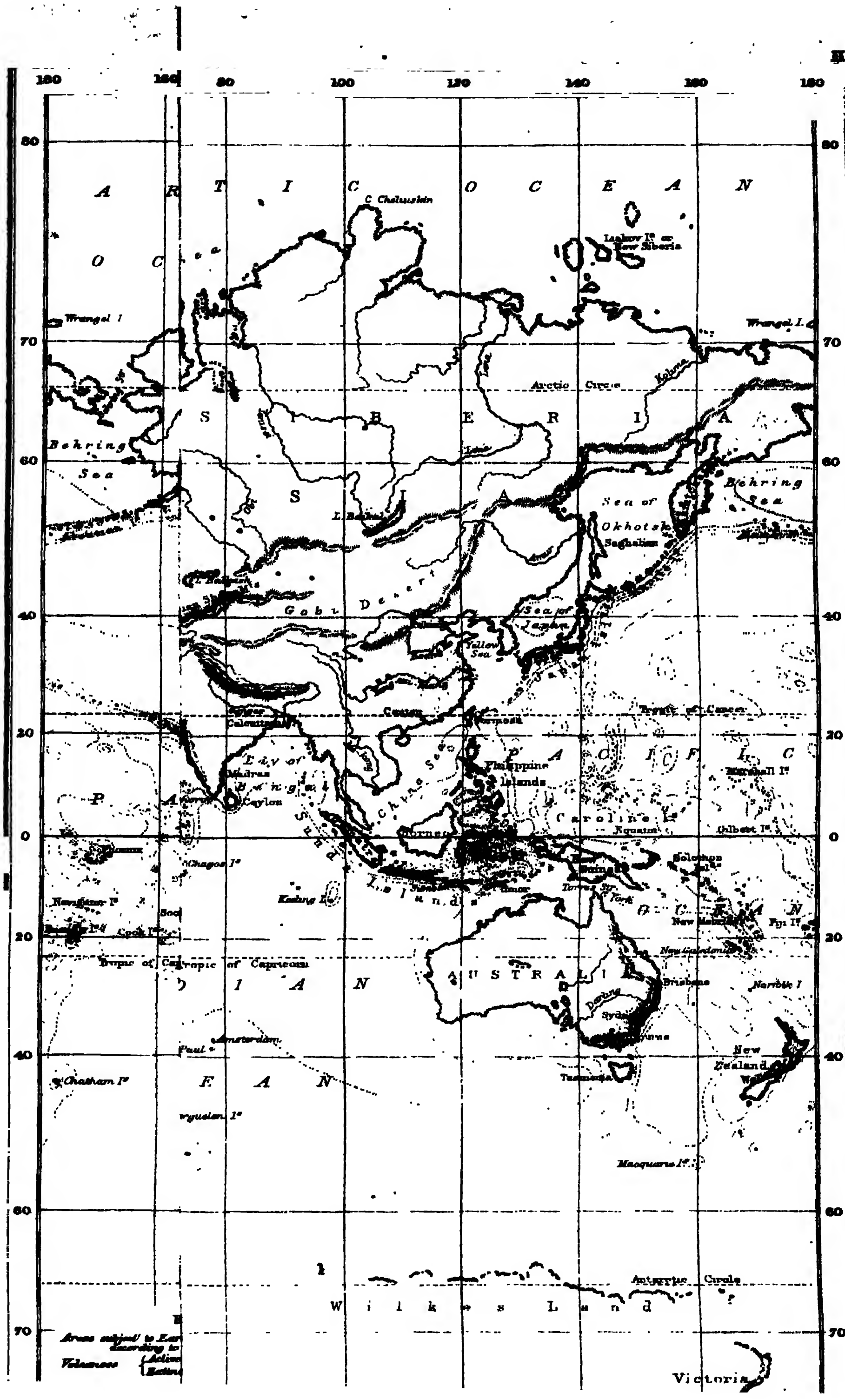
[1] 'Bull. Soc. Géol. de France,' 2nd ser., vol. xviii. p. 193, *et op. cit.*

Influx of Sea-water. When the underground springs are exhausted by the continued expulsion of the water (in the vólumes of vapour) other conditions come into operation. After a time the level of the underground waters in the sedimentary strata under the volcano will become lowered (just as the water in the water-bearing strata feeding a well is lowered by excessive pumping) to below that of the sea-level, so that the hydrostatic pressure of the inland fresh water is reduced and no longer equal to that exercised by the sea-water. The current must then become reversed; and, instead of an *outflow* from the land, an *inflow* of salt water from the sea will *necessarily* take place through the same excurrent channels that serve under ordinary conditions to carry off the fresh water, and will, through these already-made channels, find its way into the volcanic ducts. Finally, after the water-supplies become exhausted or impeded in their transmission, the lava flows quietly and unaccompanied by those violent explosions which mark the commencement of an eruption. But if, on the other hand, owing to near proximity to the sea or other conditions, the water continues to gain access slowly through the more porous volcanic materials, it may help to maintain, as in Stromboli and Kilauea, a constant slight volcanic activity. In ordinary cases, however, the inland waters after the eruption is over regain after a time their former level and again exclude the sea-water; and there is thus a return to a state of equilibrium which lasts until the strata are once more disturbed and fractured by a renewed eruption, which is heralded by the drying up of springs on the surface and the lowering of the water in some of the neighbouring wells.

Primary Cause. As for the primary cause of volcanic eruptions, I think we may look to another and independent force, viz. that arising from the slight shrinking and contraction of the earth's crust caused by the small but still measurable secular refrigeration, and its consequent pressure upon a viscous or plastic molten magma or layer beneath. That this molten matter is in some places nearer the surface than at others is possible, and that its depth is not great is probable. From time to time a state of tension of the crust finds relief in the extrusion of some of this molten matter, and then follows a state of equilibrium of longer or shorter duration. Cordier[1] calculated that a radial contraction so minute and imperceptible as one millemètre (0·0397 inch) would suffice to supply matter for five hundred of the greatest known volcanic eruptions[2].

[1] 'Sur la Température de l'Intérieur de la Terre,' p. 237.

[2] The reasons here assigned for volcanic action will be found given at length in my paper read before the Royal Society, April 16, 1885.


II.
ARCTIC OCEAN
C. Cheluskin
Liakov Is or New Siberia
Wrangel I.
Arctic Circle
SIBERIA
Behring Sea
Sea of Okhotsk
Saghalien
L. Baikal
Gobi Desert
Sea of Japan
Yellow Sea
Tropic of Cancer
PACIFIC
Marshall Is
Formosa
Bay of Bengal
Madras
Ceylon
Calcutta
China Sea
Philippine Islands
Caroline Is
Equator
Gilbert Is
Borneo
Sunda Islands
Chagos Is
Keeling Is
Timor
Torres Str.
Solomon Is
New Hebrides
Fiji Is
New Caledonia
Cook Is
Tropic of Capricorn
INDIAN
AUSTRALIA
Brisbane
Norfolk I.
Sydney
Tasmania
New Zealand
Paul
Amsterdam
Chatham Is
OCEAN
Macquarie Is
Antarctic Circle
Wilkes Land
Victoria
Areas subject to Ear... according to
Volcanoes Active / Extinct

CHAPTER XIII.

EARTHQUAKES AND CHANGES OF LEVEL.

AREAS AFFECTED. NATURE OF SHOCK. SEISMIC DEPTH. FREQUENCY OF EARTHQUAKES. VELOCITY OF EARTH-WAVE. DIFFERENCES CAUSED BY NATURE OF THE STRATA. LENGTH OF TRANSIT. THE SEA-WAVE. EARTH-FISSURES; CALABRIA; CACHAR; SAN DOMINGO. EJECTIONS OF WATER. RENDING AND SHATTERING OF ROCKS; SOUTH AMERICA; SOUTH ITALY. ORIGIN OF EARTHQUAKES. OPINIONS OF MALLET, ROGERS, AND DANA. MOVEMENTS OF ELEVATION AND SUBSIDENCE; SOUTH-WESTERN AMERICA; NEW ZEALAND; OTHER ISLANDS OF THE PACIFIC; CUTCH. RAISED BEACHES OF SOUTH AMERICA. LOCAL CHANGES OF LEVEL; PUZZUOLI; CRETE; SICILY. CONTINENTAL ELEVATIONS; SCANDINAVIA; GREENLAND; NORTH AMERICA.

Areas affected. There exists evidently a close connection between volcanoes and earthquakes. In fact they have been looked upon by many geologists and physicists merely as different manifestations of the same force, acting under different conditions, that force being the one caused primarily by subterranean heat; for although earthquakes occur in regions far removed from any volcanoes, they are most common in volcanic districts, where they precede or accompany volcanic eruptions in such a way as to indicate that between the two forms of subterranean commotion there is a close relationship.

Earthquakes, however, must be divided into those minor shocks attendant upon volcanic phenomena, and those major shocks which affect large areas independently of volcanic phenomena. In Iceland, which is in greater part of volcanic origin, and where violent eruptions are so frequent, the earthquake-shocks are only of moderate intensity, and the whole island is rarely simultaneously shaken. On the other hand, the Himalayas and the table-lands of Central Asia—in which it is doubtful whether any active volcano exists—are liable to earthquakes of great intensity; the Alps also and the Pyrenees, wholly devoid of eruptive volcanic vents, are frequently shaken, and so also is the non-volcanic basin of the Baltic. Again, the valley of the Mississippi is liable to earthquakes, though far removed from any volcano. The chain of the Andes, it is true, which is almost always in a state of commotion, is studded with volcanoes, but it would appear that the latter do not ordinarily show any remarkable activity during the occurrence of the most violent

seismic convulsions of the neighbouring mountains, and *vice versâ*. There are, however, many exceptions to this rule.

Nature of Shock. Earthquakes have been described as vibrations of the earth's crust, consisting either of a simple vibratory movement, or of vibrations accompanied by an uplift; the latter producing by far the most violent effects. They are caused by waves of the ground of greater or less amplitude, and extending over a smaller or larger area. They were supposed by Humboldt and others to be very deep-seated, and to have a

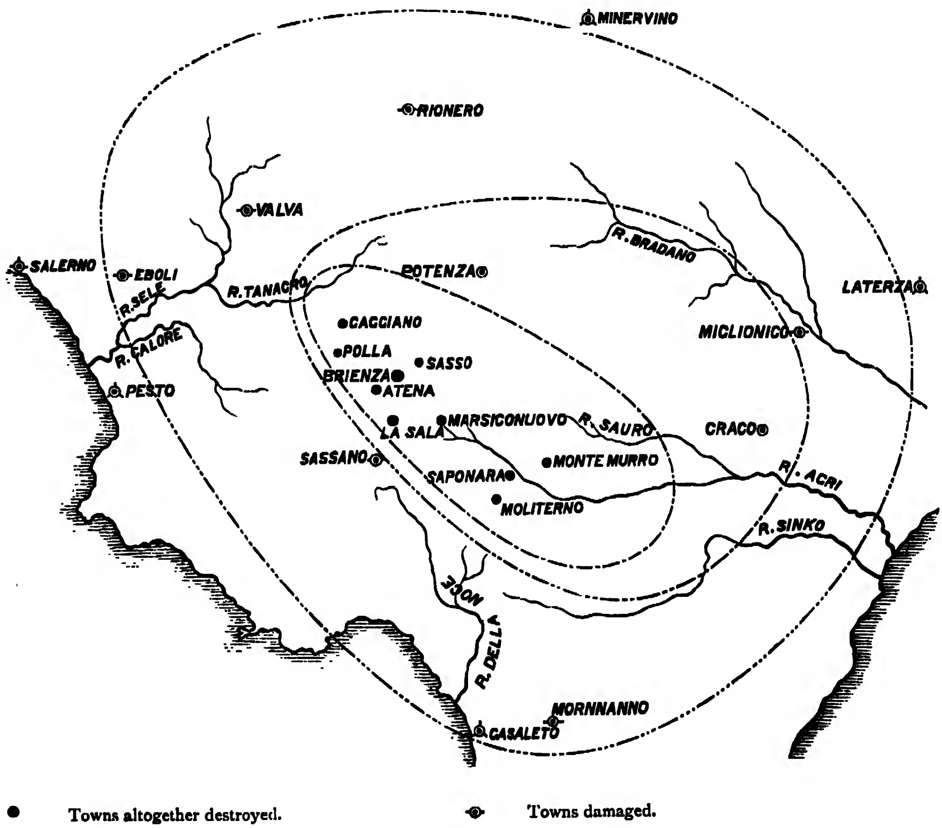


FIG. 96. *Map of the area affected by the Neapolitan Earthquake of* 1857. (Reduced from Mallet's map.)

linear direction for a longer or shorter distance; but the careful observations made by Mallet[1] in 1858, after the last great earthquake in South Italy of 1857, led him to a different conclusion. This case affords an excellent illustration of an earthquake in a volcanic district.

According to him, the earthquakes can always be traced to a centre from which the shock radiates to the circumference. The centre of this

[1] 'The great Neapolitan Earthquake of 1857.'

Neapolitan earthquake was at Caggiano,—a village sixty miles S.E. of Naples,—from which point it formed an ellipse, of which one diameter was sixty miles, and the longer diameter about ninety.

The towns and villages near the centre of the shock suffered dreadfully; many of them were almost completely demolished. The witnesses of the shock spoke of it as, first of all, a lifting-up movement, and immediately afterwards it became horizontal and vibratory. It was succeeded by a second shock half-an-hour later, which was described as vertical. It was accompanied or rather preceded by sounds like the sighing of the wind; at other places they were likened to the rumbling of a carriage. At Salerno, on the other hand, the shock was so slight as not to throw down furniture. It was slightly felt at Naples, while beyond it was scarcely perceptible.

Seismic Depth. Mr. Mallet estimated the maximum depth of the focus at 49,359 feet, or $8\frac{1}{2}$ geographical miles; and the minimum depth at 16,705 feet, or $2\frac{3}{4}$ miles. He elsewhere remarks that the greatest probable

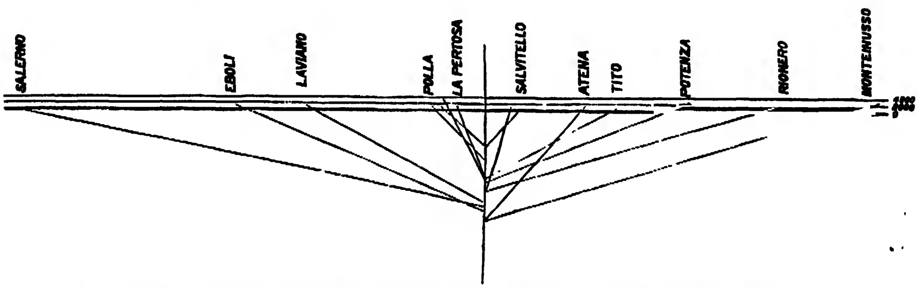


FIG. 97. *Diagram of mean wave-emergences and deduced mean focal depth.* (Mallet.)
o marks the sea-level, and the figures give the height above it in feet. The horizontal distance=62 geographical miles, and the depth of the deepest seismic vertical=about 62,000 feet.

depth of any earthquake impulse occurring in our planet is limited to 186,176 feet, or 30·64 geographical miles. He measured the depth by the angle of emergence on opposite sides of the centre of the shock.

In the case of the great Cachar (Bengal) earthquake, of January 1869, which was the subject of an elaborate inquiry by the late Dr. Oldham[1], the depth of the seismic focus was calculated to have been not less than twenty-five miles, but more probably about thirty, and might have been as much as thirty-five miles.

Mr. Mallet pointed out that we are not to confound the velocity of transit of the shock and the velocity of the wave-particle at its maximum. The first is about half that of a cannon-shot, and the latter, which does the mischief, is not so great as that with which a man reaches the ground when he jumps off a table. With respect to the former, he found that the time of transit from Vietri to Naples was $8^m\ 46^s$, which, taking the distance at 68 geographical miles, gives (corrected) 808 feet per second.

[1] 'Mem. Geol. Survey of India,' vol. xix. part 1.

Sounds were heard with, or nearly along with the shock over an area equal to more than 2500 geographical square miles.

Mr. Mallet considered that the centre of the Neapolitan disturbance was not in one given point, but that there was a line 7½ miles long, from which the shock radiated, the main focal point being near Caggiano. And he thought it probable that the sounds were 'due to the rending, and probable filling with high-pressure steam, of a rent commencing at or near the main focal point, and extending about 7½ geographical miles in length,' though the extreme dimensions of the rent considerably exceeded this, and was probably coincident with some pre-existing line of fissure.

With the exception of some openings on mountain-heights, presently to be mentioned, there were but few rents formed on the surface of the ground, and they were all small, not exceeding a few inches in width and a few feet in depth, and were transverse to the direction of the wave-path. There were, however, a great many landslips in yielding and argillaceous strata, and a number of rock-falls, some of them very important, whereby thousands of tons of débris were thrown down the slopes of the hills and into the adjacent valleys. Moreover, an instance is given of a deep narrow rent, two miles or more long, in hard limestone, produced apparently by some older shock.

Mr. Mallet enters into a minute detail of the way in which the shock affected the falling walls and houses, and he deduced from those observations the direction of the earthquake-wave.

Much more might be said of the destructive effects of earthquakes, but we have only to view them in relation to their bearing on geological phenomena, and to the cause which produces them.

Frequency of Earthquakes. They are of far more common occurrence than might be supposed. M. Perrey gives a list of 2329 earthquakes known up to 1801, and of 926 from 1801 to 1845; but other records make the number still higher. Mr. Mallet has enumerated some 6000 to 7000 recorded shocks in Europe alone. Italy is the country where earthquakes are most common, and Russia where they are most rare, in fact, where they are almost unknown. According to Prof. John Milne, one of the countries where they are extremely frequent is Japan; often a day does not pass without one or more shocks in some part of the islands.

In Western South-America they are not only often of fearful intensity but also of frequent occurrence. Mr. W. J. Henwood, who resided for several years in the mining districts of the Andes of Chili, said that, during his sojourn there, more than three days seldom passed without an earthquake. (See Map No. II, p. 216, in which the distribution and relative force of the earthquakes are shown.)

Taking the earthquakes between the years 306 and 1844, M. Perrey

found that 1712 took place in winter and spring, and 1335 in summer and autumn.

Velocity of Wave. The rate at which earthquakes travel depends upon the elasticity of the rock and the elevation and contours of the surface. In contrast with the Neapolitan earthquake, which travelled only at the rate of nine miles per minute, is that which in 1843 traversed the United States from its North-Western boundary, beyond the Mississippi, to Georgia and South Carolina, at a rate of thirty-two to thirty-four miles per minute. The rate of wave-travel of the Cachar earthquake was calculated by Dr. Oldham at about eighty-three miles per minute, but he considered the data to be somewhat uncertain.

Differences caused by nature of the Strata. Though the shocks are propagated with greater rapidity through solid rocks than through those which are soft and friable, the effects on buildings situated on the latter class of strata are far more disastrous than when they stand on hard and compact rocks. In the instance often quoted of the destruction of Port-Royal in Jamaica, in 1692, it would seem that the whole of the town was situated on sandy flats. The fort, which stood on a rock, alone escaped.

In the Tuscany earthquake, referred to further on, the villages situated on hills of sandy and argillaceous strata suffered greatly, whereas those on the higher limestone hills were but little injured. Spallanzani says that in the great earthquakes of 1783 all that part of Messina which stood on the soft and yielding strata of the plains was entirely destroyed, but that the houses on the declivity of the hills, on granite, were only partially damaged.

Mr. D. Sharpe found, on mapping the geology of Lisbon, that the greatest force of that disastrous earthquake had been confined to the area of 'Almada clay,' on which the lower part of the town stood. Not a building escaped. Those upon the slopes of the Almada sands and limestones suffered also severely. All the buildings, on the contrary, on the Hippurite limestone and the basaltic rocks escaped entirely; the line at which the force of the earthquake ceased to be destructive corresponding exactly with the boundary of the softer and less coherent Tertiary beds [1].

Length of Transit. Earthquakes have been known to travel along the west coast of South America for a length of 2000 miles; and the great Lisbon earthquake of 1755 was felt over nearly the whole of Europe, and the houses in North Africa and even in Iceland were shaken by it.

The Sea-wave. The effects produced by the great sea-wave which so often accompanies earthquakes are of considerable geological importance. During the disastrous Lisbon earthquake, the sea came into the Tagus in a wave sixty feet high, sweeping everything before it. At Cadiz it was

[1] 'Trans. Geol. Soc. of London,' 2nd ser., vol. vi. p. 132, 1842.

thirty feet; on the shores of Madeira eighteen feet; and on the coast of Cornwall eight to ten feet high; and it was even apparent on the North of Scotland, while westward it extended to the West-India Islands.

As an instance of the powerful denuding effects of these waves, both on the land and on the sea-bed, the account given by Commander Adams[1] of what occurred during the great earthquake of Samoda (Japan) in 1854 will serve as an illustration. The waters in the bay were violently agitated; they then retreated, leaving the bottom nearly bare where usually there is thirty feet of water. The sea then rushed in with a wave thirty feet high, overflowing the town to the top of the houses, destroying and sweeping away in its retreat everything before it. This was repeated five times. The anchorage in the bay was reduced from thirty-six feet to four feet, and all the holding-ground of silt and mud was washed out to sea, leaving a bottom of naked rocks only. This earthquake drove oceanic waves across the Pacific to Oregon and California[2].

In 1751 an earthquake-wave deluged the port of Callao, sunk twenty-three vessels, and carried a frigate some distance inland. The oceanic wave extended half-way across the Pacific to the Hawaian Islands, a distance of 6000 miles.

In 1861 at the island of Batoa, in the Eastern Archipelago, the sea rose and rushed with great velocity over the land, destroying everything on its passage, and carrying with it on its retreat 700 of the inhabitants, denuding and channeling the surface, and uprooting the luxuriant vegetation with which the land was covered. At Pulo Nyas the same earthquake-wave rased a fort on the coast, and swept away to sea the entire garrison.

Earth Fissures. Amongst other earthquake phenomena the earth is reported in some cases to have opened and formed deep and wide fissures, in which animals and men were engulfed; but, while some observers consider these fissures to be primary results, due to the shock, others contend that they are due to secondary causes, connected with the physical and stratigraphical structure of the country.

The great earthquake of Calabria in 1783 was remarkable for the destruction caused by incidents of this nature. Dolomieu, who visited the country a year after the event, and who was careful to guard against the exaggerations so common amongst the people on these occasions, describes the aspect of the country and the scenes of wreck which he witnessed. His account shows how much was due to the geological structure of the country. The central range of the Apennines there consists of granite, on the flanks of which, and stretching down to the sea-board, is a high tract of sandy

[1] Hawkes' 'American Expedition to Japan,' vol. i. p. 509.

[2] From data obtained on this occasion respecting the velocity, height, etc. of the earthquake-wave, Professor Bache calculated the average depth of the Pacific to be about 13,000 feet.

and soft calcareous Tertiary beds. From the high and bare granite mountains numerous streams descend, which have cut chasms and ravines through the Tertiary strata to a depth, in some places, of 600 feet. The sides of these narrow valleys are usually abrupt and sharp, while the intermediate ground presents high and flat plateaux.

The focus of the shock was considered by Dolomieu to have been under the granitic axis. The inclined Tertiary strata slipped in places from the face of the granitic mountains, and in one instance a large chasm, nine miles long, was formed between the soft Tertiary strata and the solid nucleus. But the main body of the chasms and fissures were opened along the flat plateaux, in a direction parallel to the course of and near the valleys, where, from the want of support, the detached segments of ground skirting the gorges often slipped down or toppled over into the valleys below. There the rivers became obstructed and temporary lakes were formed. The course of some rivers was altered; and other rivers were dried up. In some places water spouted from the earth to the height of several feet, carrying with it mud and sand.

Mallet's experience agreed very much with Dolomieu's, but with few important exceptions.

A more recent illustration of these effects is furnished by the Cachar earthquake, before referred to. Dr. Oldham clearly showed that the rending and fissuring of the ground, general throughout the large tract of flat ground adjacent to the rivers Soorma and Barak, was due to the slipping of a great stratum of clay, some twenty-five to thirty feet thick, overlying a bed (three or four feet thick) of sandy ooze full of water. The rivers have cut gorges through these beds to a depth of from forty to fifty feet; and, when the water is low, they flow between high overhanging cliffs of these strata. The earthquake happened when these conditions of low water prevailed, and consequently the great overlying mass of clay, wanting support, slid over its oozy bed toward the river, and a number of fissures more or less parallel to their course were thereby formed. They were most numerous near the river-banks, and none were made in the solid rocks, that rise at a distance beyond these extensive *Bhurti-land* plains. Dr. Oldham came to the conclusion that the great earth-fissures were in every case purely secondary results of the earthquake shock.

The evidence of such geologists as Dolomieu and Oldham is conclusive with respect to the ground they describe, and some seismologists have seen in these facts corroborative evidence that any direct production of earth-rents or fissures by the transit of the earthquake-wave is physically impossible[1]. But surely so general a conclusion may be questioned. If the existence of earth-waves be admitted, although their height and width have

[1] Mallet, 'Quart. Journ. Geol. Soc.,' vol. xxviii. p. 261.

yet escaped exact measurement, there is nothing improbable in the fissuring of the ground and the closing of the fissures as the wave passes onward along the surface (Fig. 96, p. 225) and the uplifted surface returns to its original levels. It will depend on the curve. That these waves are at times of some height, and of considerable amplitude, is evident from the visible rolling of the ground, the movement of the land, and the swaying of the trees, even to the extent of their tops nearly touching the ground, not unfrequently witnessed. Colonel Godwin-Austen, who was at Assalo during the Cachar earthquake, says that the last waves were 'very like those of a gentle swell at sea,' and that 'it was a curious sight to see the way in which the waves passed over the forest-clad mountain-side, as if the trees were bowed by the passage of a mighty wind[1].'

M. Chas. Deville, in his report[2] on the San Domingo earthquake of 1843, states that numerous fissures were formed, some of which remained open at the time of his visit, while others were closed. The substratum consists of a calcareous shelly tufa of recent origin. In some of the lower grounds these fissures in closing projected water to the height of five feet, throwing out mud and débris of the rocks below. Similar phenomena were exhibited in an adjacent volcanic island: considerable landslips took place there on the cliffs and on the volcanic hills in the interior, leaving large bare denuded surfaces of rock.

After the great South-American earthquake of 1819, Captain B. Hall saw near Chimba large fissures, caused by the shock, still open in the ground. Another observer describes similar results at Conco north of Valparaiso.

In 1854 an earthquake totally destroyed the town of San Salvador in ten seconds. This capital was built on a small plateau of volcanic ashes and scoriæ[3]. The ground around is traversed with fissures and ravines, formed during successive earthquakes, and since gradually enlarged by the streams which flow through them. These accounts, however, want details.

Ejections of Water. Another competent observer, M. Pilla, describing[4] the effects of an earthquake which took place in Tuscany in 1845, says that at Lorenzana, near Pisa, he found, soon after the shock, a number of small funnel-shaped cavities (entonnoirs), from a few inches to a foot in diameter, from which water flowed, and which he compares to natural artesian wells. The water was cold, and the cavities lay in straight lines across the valley, and were apparently at right angles to the direction of the earthquake-wave. There were six of these bands, and along one of them there were as many as twenty-four water-holes in one line. Judging

[1] Oldham, *op. cit.* p. 41.
[2] 'Comptes Rendus,' vol. xvii. p. 1283.
[3] Dollfuss, 'Voyage géologique dans la République de Guatemala,' p. 16.
[4] 'Comptes Rendus,' vol. xxiii. p. 468.

from the depth of the adjacent ordinary surface-wells, he inferred that the water proceeded from a water-bearing stratum more than forty feet below the surface. The ground consists of soft *molasse* and blue marls, while the surrounding hills are of sub-Apennine limestone.

We may readily conceive in this and the many other similar cases recorded, that if the earthquake-wave, as it passes along, opens a fissure reaching down to an underground water-bearing stratum, the water would rise at once in the fissure to a height dependent upon the height of the stratum at its outcrop; and, if that be at a higher level than the level of the fissure, the water would rise to the surface and overflow. In such a case then, on the fissure closing after the passing of the wave, the water that had flowed in would be forcibly ejected, and detached water-channels might be left temporarily along the line of fracture at the points of greatest scour and wear.

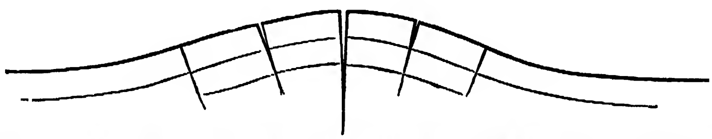


FIG. 98. *Diagram showing the possible opening of the ground caused by the passage of an Earthquake Wave.*

Rending of Rocks. Other seismic effects of especial importance in their bearing on some of the present features of mountain ranges are the rending, shattering, and dislodgment which the rocks undergo. These effects are from their situation less frequently noticed than the other phenomena, and for the reasons before named it is not always possible to be sure whether the fissures are due to landslips or directly to the shock. Mr. Caldcleugh states that during the great earthquake in Chili, of February 1835, fissures several feet in width and depth were formed in the ground,—that throughout the provinces of Canquens and Concepcion the whole surface was rent and shattered,—that cliffs on the coast 150 to 200 feet high were split and fractured in all directions, and huge masses precipitated below. This earthquake was closely connected with neighbouring volcanic activity. Several of the great volcanoes of the Cordillera were active, both previous to and during the earthquake convulsion. A violent eruption of Coseguina commenced in the preceding January, and on the twentieth of the same month the volcano of Osomo [1], to the N.E. of Chiloe, burst out with great fury.

Of a previous earthquake (1647) in Chili, it is recorded that its violence was such that the fall of rocks in the mountains modified their form and size. In another account it is said that the ground opened and that large quantities of water were ejected from the fissures [2].

[1] *Op. cit.* p. 21.

[2] A. Perry, 'Soc. Imp. d'Hist. Nat. etc. de Lyon,' 1854, p. 8. Another observer says that at the moment of the great shock (of 1835), great columns of water resembling garden fountains

Captain Head[1] mentions that, when at the mines of Petorca in Chili shortly after the great earthquake of 1822, he was informed that the mine was shaken to its base and large fragments of the lode thrown down, while on the surface great blocks of rock were detached from the summit of the mountain and rolled down its sides; and that a cloud of dust, so thick that one could hardly see one's hand, enveloped everything. Many similar instances have been recorded in western South America. One writer speaks of the earth opening and vomiting water; another (without giving particulars), of a mass of granite which was fissured; and others notice differences of level on the sides of the fissures to the extent at places of as much as ten feet. Nor are such phenomena wanting in the flatter and less disturbed country on the eastern side of the Andes. In 1844 an earthquake shock was felt over a length of a 1000 miles across the Pampas of Tucuman and Salta. The ground opened in many places and ejected quantities of sand and water.

Captain Gill states that when he visited Bat'ang in China, after the frightful series of earthquakes lasting over several weeks by which the district was devastated in 1871, he found that in the town itself not one house was left standing, and that the hill sides around were rent and torn and huge heaps of débris hurled from the mountains had in many places buried and obliterated the ancient paths[2].

Mr. Mallet reckoned rock-fractures, falls of rocks, land-slips and earth-fissures, and alterations of water-courses generally amongst the secondary effects of earthquakes; but he also remarks, in speaking of the mountainous Apennine region of Southern Italy, that a shock passing through an elevated country of lofty peaks and deep gorges—the higher regions having bare surfaces of shattery rock—may bring down millions of separate fragments, great and small, which shall roll and bound down the steeps and shatter in repose in the lower valleys thousands of feet below their former position[3].

Speaking of a deep gorge near Arena Bianca, at an elevation of 3158 feet, he says there were there beds of the very hardest and toughest rock (such as with difficulty he broke specimens from with the hammer) fractured for many yards in depth (fully 30 yards visible) and over a great length, and yet free from other signs of violence or from any other sensible disturbance of position. It realised forcibly to his mind the enormous power of the impulse of shock, with even the moderate velocity

were thrown up to considerable heights. Perry, *op. cit.*, p. 133. Accounts of this description are often discredited, but in many cases I fail to see on what grounds, except that the popular exaggerations are apt to throw discredit on statements which may nevertheless have a foundation of truth. Many of the records are by trustworthy and competent observers.

[1] 'Rough Notes on the Pampas,' p. 207.

[2] 'River of the Golden Sand,' vol. ii. p. 188.

[3] Mallet, *op. cit.*, vol. ii. p. 368.

of the Neapolitan earthquake, when acting on great masses at free and outlying surfaces; and he thought it suggestive of the much more potent effect that must occasionally be produced in loftier ranges subject to still more powerful influences.

The origin of Earthquakes. Mr. Mallet considered that the 'earthwave-shock' may be the result of a sudden impulse or blow,—such as a sudden volcanic outburst, sudden cracking of a mass of rock in a state of tension, sudden generation of steam from water in a spheroidal state, or sudden condensation of steam under pressure of sea-water. 'Such a sudden impulse would always cause a *wave*, that is a *rise and fall*, either in solid, liquid, or gaseous substances[1].'

The origin of earthquakes has also been referred to the falling in of portions of the earth's crust into great subterranean cavities, and to rain-water, or the waters of the sea, gaining access to the underlying heated nucleus, whereby steam is generated, which rends and dislocates the incumbent crust. But we have no reason to suppose that any great subterranean cavities exist under the crust of the earth; nor can I see, as I have before explained, how water can percolate to a depth sufficient to reach the nucleus, or in sufficient quantity, except, if it were possible, by means of those very disturbances which are presumed to be caused by the earthquake itself. If even from any cause a cavity existed into which the water could pass, it is doubtful whether any explosion of steam could take place at the depth to which water might percolate, owing to the enormous pressure to which it would be subjected.

Nevertheless it would seem possible that cavities may exist at depths beneath the surface, but only in a small and very exceptional way. Mineral veins, which are rents that have extended to unascertained depths and have been partly filled with débris and partly with mineral matter, have occasionally open spaces left in them. In Cornwall they have been met with at considerable depths and always filled with water (see Chapter XVIII). Similar cavities have also been found in fault-veins. The question arises whether it would be possible, under any circumstances, for this water to flash into steam, and whether, if it were so possible, it would be condensed in passing through cooler overlying strata without rising and escaping at the surface. Cavities of the sort above described could however only exist along lines of fault and of mineral veins. A few local ones might also exist in the rents caused by volcanic eruptions, and though these may in some cases afford a key to the local shocks, always of limited range, so common in volcanic centres, they fail to explain the wider phenomena of great continental earthquakes. Cavities in limestone rocks are not possible beyond a certain depth. In some volcanic areas there does, however, seem to be a connection

[1] *Op. cit.*, vol. i. p. 405.

between the surface-waters and local earthquakes. In the district around Lake Ilopanga in San Salvador—a lake which occupies the site of a volcanic crater—earthquakes are common. But here they are said always to occur when the water of the lake rises (and its pressure increases). The Spaniards used to cut trenches to facilitate the escape of the water, and for a century no earthquakes occurred. After this precaution was neglected the waters rose to a higher level, the disturbances resumed, and in 1880 a new crater about 70 feet high was thrown up in the centre of the lake. With the continuance of the eruption the level of the water in the lake again gradually lowered [1].

The late Professor H. D. Rogers [2] considered the earthquake-wave to be due to a solid crust moving on a fluid substratum, and that it consists of a rapid undulatory-like movement of the ground, accompanied by a short vibratory jar, or tremor, the one extending to as great a distance as the other. He rejected altogether the idea of a single vibratory jar, which, he contended, would be single, short, and violent.

The great earthquake of 1843, in the United States, was felt in one direction from Georgia and South Carolina to beyond the Western outposts, and in the other from Natchez to Iowa—800 miles both ways, and perhaps more. The wave was of great amplitude—10 to 25 miles; and Professor Rogers shows that it was felt simultaneously in a narrow belt, proceeding in parallel lines from a central axis, in a N.N.E. direction from Alabama through Nashville and Cincinnatti. He states that it traversed 270 miles in 8 minutes and 8¼ seconds, or at the rate of about 32 miles a minute. He also remarks on the occurrence of alternate opening and closing of enormous parallel chasms of great depths and perpendicular to the course of the undulations.

For my own part I am more disposed to share the view expressed by Dana, that the tension and pressure, by which the great oscillations and plications of the earth's crust have been produced, have not yet wholly ceased; and that this is generally the most probable cause of earthquakes. The uplifting of great continental tracts and mountain ranges must have always left the interior of the crust in a state of unstable equilibrium, and any slight slide or settling along an old fracture, or in highly disturbed and distorted strata, would be attended by an earthquake shock.

In volcanic areas the removal of the large volumes of molten rock from the interior to the surface must produce settlements and strains which might also result in some of those minor earthquakes to which volcanic districts are so subject. Where we have the two conditions combined, as they are in the Andes of South America, there earthquake phenomena are, as we should expect, developed on the grandest and widest scale.

[1] 'Nature,' vol. xxii. p. 129.

[2] 'Amer. Journal Sci. & Art,' vol. xlv. p. 341.

These views are not inconsistent with the occurrence of those other, sometimes occasional, sometimes persistent and gradual, slight movements of elevation and subsidence that we still witness on the surface of the globe, and admit of exact measurement.

Movements of Elevation and Subsidence. Although the earth, in this its present stage, has reached a state of comparative stability, small changes of level are still taking place. They are of two kinds.

1st. Those which take place in volcanic districts, and which are usually accompanied by earthquake movements.

2nd. Those slow and secular movements, independent of volcanic and earthquake phenomena, and extending, at an imperceptible rate, over large areas, and during those indefinitely long periods that carry us back to the later geological times.

The first section is connected with the phenomena we have just been considering, and may be divided—1st. into sudden elevations or subsidences—elevations 'per saltum'; and 2nd. slow and continuous elevations.

Amongst the best-known instances of the former are those which have taken place on the western coasts of South America. During the great earthquake of 1822 the coast was suddenly raised for a distance of 1200 miles to a height varying from 3 to 4 feet above its former level. And again, in 1835, the coast of Chili underwent a sudden elevation, at the time of another great earthquake, of 4 to 5 feet; but, in the latter case, there was a subsequent slow fall or settlement, and the amount of rise gradually diminished, so that two months afterwards the coast was within two feet of its former level.

The coast of New Zealand has been more than once raised within the last century. During an earthquake in 1855, a large tract near Wellington was upraised from 3 to 4 feet; at the same time a fracture was formed, and the strata were faulted for a considerable distance to the extent of several feet.

Hochstetter[1] observes that this rise was not general over New Zealand, and that there were proofs that, while on the eastern side of the islands the level of the land was being raised, on the western side the level sank. An axis of equilibrium seems to pass through these islands, curving round parallel to the Australian coast-line, crossing between New Caledonia and the Loyalty group, and traceable through the Solomon Islands to New Guinea.

Mr. Sawkins[2] states that in 1854, in consequence of an earthquake in the Coral Island of Tongataboo, one of the Friendly Islands, the N.E. portion of the island was tilted down at an inclination sufficient to produce

[1] 'Geology of New Zealand,' 1864, p. 108.
[2] 'Quart. Journ. Geol. Soc.,' vol. xii. p. 383.

an encroachment of the sea for nearly two miles inland, whilst the western coast rose several feet. Some parts of the island show elevation to the extent of 116 feet. A volcanic island is said to have risen at the same time at a distance of 30 miles from land. Mr. Sawkins considers that in the Pacific the amount of elevation has exceeded that of subsidence. At Tahiti raised coral-beds alternate with volcanic ashes.

A well-known case of seismic disturbance is that of Cutch, in the delta of the Indus, where the ground after the earthquake of 1819 was depressed in one part 17 feet, while another tract, 50 miles in length, was raised 10 feet above its original level. Another case is that of the 'sunk ground' of the Mississippi valley, 80 by 30 miles in extent, which subsided several feet during the prolonged earthquakes of 1811–1812[1].

Besides these instances, which have occurred within the present century, Darwin noticed raised beaches, at various heights, up to 1300 feet, on the western coast of South America[2]. They occur at several levels; those at an elevation of more than 500 feet being faintly marked, but still containing the common species of shells, with fragments of spines of the Echini living in the adjacent sea. The only difference noticed by Darwin was in the proportional number of the several species in the raised beaches and on the present beach respectively. Some species, which were rare formerly, are common now, and the reverse. At the same time it is evident, from the circumstance of the finding, near Callao, of remains of human art (such as plaited rush, string, and Indian corn) in a bed of marine shells, 85 feet above high-water mark, that elevation to this extent has taken place since 'Indian man inhabited Peru.'

He also noticed a case where a church, which had stood within reach of the sea waves, had been raised 19 feet since 1817. He says that in many parts of the coast of Chili and Peru these marks of the action of the sea occur at *successive* levels on the land, showing the elevation to have been interrupted by periods of comparative rest. But whether the successive elevations themselves were sudden or gradual, he would not decide. From the occurrence of similar terraces in Eastern Terra del Fuego, Darwin thought 'that the entire breadth of the continent in Central Patagonia has been uplifted in mass.'

Although we here have evidence of small movements of elevations frequently repeated, until eventually the total amounts to 1300 feet, still this does not affect the great question of the elevation of mountain-chains. It represents the elevation of a continental area, and not the anticlinal or ridge-like elevation which alone would characterise the upheaval of a mountain chain. In no case did Darwin show that these raised sea-beds follow

[1] For full particulars of these and many similar cases the reader should consult Lyell's 'Principles of Geology,' 10th edit., chapters xxviii, xxix.

[2] 'Geological Observations on parts of South America,' 2nd edit., chapter ix.

the irregular gradients of a mountain axis, but that they form terraces, irrespective of the contour of the surfaces, and following the sides of the inland valleys and of the cliffs and hills of the coast-line. They indicate elevation 'en masse,' and not in ridges or anticlinals.

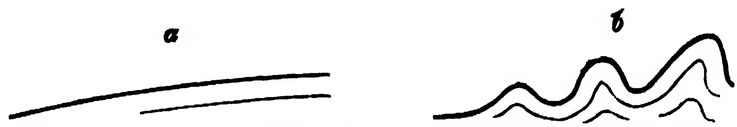


FIG. 99 *Diagram showing the distinction between Continental (a) and Mountain (b) Elevation.*

Local Changes of Level. With respect to the quiet rise or subsidence of the land over small areas in volcanic and earthquake districts, the Temple of Jupiter Serapis, which stands at a short distance from the sea, at Puzzuoli, near Naples, and was built about nineteen centuries ago, offers a noted instance. Its original position may have been close to the sea; and, from the circumstance of an older floor having been found 5 feet below the later floor of the temple, it is probable that the sea was already gaining on the land at the period of its foundation[1]. At some much later period, after apparently an eruption of volcanic matter which buried the lower part of the temple, a depression of the land took place to the extent of between 20 and 30 feet, and for a considerable time the temple stood immersed in the sea, as shown by the lithodomous perforations of marine shells which encircle the standing columns in a broad ring 9 feet deep, at a height of 12 feet above the floor. This was followed by a movement of elevation which raised the floor of the building to a height of 2 feet above the sea-level. Again, since the beginning of this century, a movement of depression, estimated at about 1 inch in four years, has set in, and in 1870 the sea had again come in and covered the floor to the depth of a few inches. The eroded band, or that portion of the shaft perforated by boring shells, shows the height at which the water must have stood for a considerable time.

An analogous case is mentioned by Admiral Spratt and Prof. Edward Forbes as occurring in Asia Minor, where, in the bay of Macri, an ancient sarcophagus, still standing partly in the water, is bored by marine animals to a third of its height above the water, indicating therefore a subsidence and subsequent rising of the land.

Admiral Spratt describes several parts of the coast of Crete, which have in recent times suffered either elevation or depression. On the Isthmus of Spina Longa are the remains of a Greek city, a large part of which now lies beneath the sea-level, the subsidence amounting to 6 or 8 feet or more; whereas on the western side of the island there has been a movement of elevation, amounting in some parts to as much

[1] Babbage, 'Quart. Journ. Geol. Soc.,' vol. iii. p. 186; Lyell, *op. cit.*, vol. ii. p. 165.

as 20 feet; and he gives a plan of the ancient port of Phalasarna, of which the entrance-piers remain standing at an elevation of 16 feet above the present sea-level[1].

Gemmellaro considers that the south coast of Sicily has been raised as much as 14 mètres in recent times, because at that height he found Serpulæ and other marine shells still adhering to the rock on the hills adjacent to the coast. There is, in fact, all round the Mediterranean[2] sufficient evidence of the comparatively recent elevation of the land, and of the formation of shelly conglomerates, in many cases since the time of the Romans.

With regard to the second kind of earth-movements, or **Continental Elevations**, Scandinavia affords a remarkable and noted instance of an extensive and mountainous country, 1200 miles in length, subject during long ages to slow secular changes of level. At present, however, we have only to deal with that which comes within historical time. Sir Charles Lyell estimated the rise at Gefle, 90 miles north of Stockholm, to be at the rate of about 2 to 3 feet in a century. This is the extreme amount of elevation, which at the North Cape and also on the eastern side of the Gulf of Bothnia is just slightly perceptible. At Stockholm it hardly exceeds 6 inches in a century; while further south the upward movement gives place to one in an opposite direction, for 16 miles south of Stockholm the land is stationary. But further south near Trelleborg a large stone was found to be 100 feet nearer the sea in 1836 than when measured by Linnæus in 1749; and at Mälmo the submergence has been such that the sea overflows one of the streets. It would thus appear that, while the north of Scandinavia is rising, the southern portion is slowly subsiding[3].

On the south-west coast of Greenland, for a space of more than 600 miles from north to south, the land has been slowly sinking during the last four centuries. Old buildings on the shores of the mainland are now under water, and low islands have been submerged. Further north, and extending over nearly the whole of the lands bordering the Arctic seas of North America, there has been within comparatively recent times a slow upheaval whereby the coasts have been raised to the extent of 200 to 300 feet.

Labrador, Hudson's Bay, and Newfoundland likewise present evidence of elevation. Proceeding further south there is again clear evidence of

[1] 'Travels and Researches in Crete,' vol. ii. p. 232.

[2] Professor E. Hull has recently drawn attention to a very remarkable *Raised Beach*, with numerous shells of existing species, 150 to 250 feet above the sea-level, on the north coast of Syria. 'Nature' for August, 1884.

[3] More exact measurements have recently been concluded, and the results published by the Swedish Academy of Sciences. It appears from these that during the last 134 years the northern part of Sweden has risen about 7 feet; that there has been no change at Bornholm; while the southern fringe of the Baltic has been slowly sinking.

submergence. On Prince-Edward's Island Dr. Gesner[1] describes a recent peat-bed 19 feet under the sea at low tide; and states that in the Island of Cape Breton the sea now flows within the walls and over the site of Louisberg—a town destroyed in 1758. In Nova Scotia, on the contrary, the land seems to be slowly rising, although it is not so apparent as in the sister province of New Brunswick. Dr. Gesner estimates that there is at the mouth of the River St. John, and at the city of the same name, an area of 20 square miles which has undergone in the centre an elevation of about 18 feet. To the south of the province there seems to have been a submergence of the like extent. Further south, again, on the boundary-line between Canada and the United States, an elevation of the land has taken place, and this is succeeded at Holm's Hole, Martha's Vineyard, the island of Nantucket, and Portland by a subsidence, which has fringed the coast at places with submerged forests. This subsidence is prolonged southwards to the coast of New Jersey, where, within the sixty years previous to his writing, Dr. Gesner estimated it to have lowered the land to the extent of from 5 to 12 feet; it then dies out and does not seem to extend further south. Elsewhere in the United States and in Canada it does not appear that there has been any material change in the relative level of the land.

Dr. G. Dawson has given an account of some of the more recent changes in level which have taken place on the coast of British Columbia. While it would appear that the coast of North-Western America has undergone an elevation of from 200 to 300 feet since the Glacial Period, there is reason to believe that a slight movement of depression to the extent of 10 to 15 feet, and extending from Prince William's Sound to Vancouver and Washington Territory, has lately been for some time in progress. In the last-named district there are groves of dead *Thuja gigantea* now standing in the tide meadows[2].

Equally remarkable has been the slow upheaval of the Asiatic coast of the Polar seas, of Spitzbergen, and Nova Zembla. These lands have in many places been raised to the extent of 300 feet or more, channels have become blocked, and islets off the shores have, within the memory of man, become joined to the land.

The reader will find in the Coral-island map, p. 234, a general approximate delineation of the coast areas affected within modern times by upheaval and subsidence. Their actual extent and amount yet requires determination. It is also likely that in many of those areas there may be interruptions of continuity caused by neutral zones.

[1] 'Quart. Journ. Geol. Soc.,' vol. xvii. p. 381.
[2] 'Canadian Naturalist,' vol. viii. No. 4.

CHAPTER XIV.

CORAL ISLANDS.

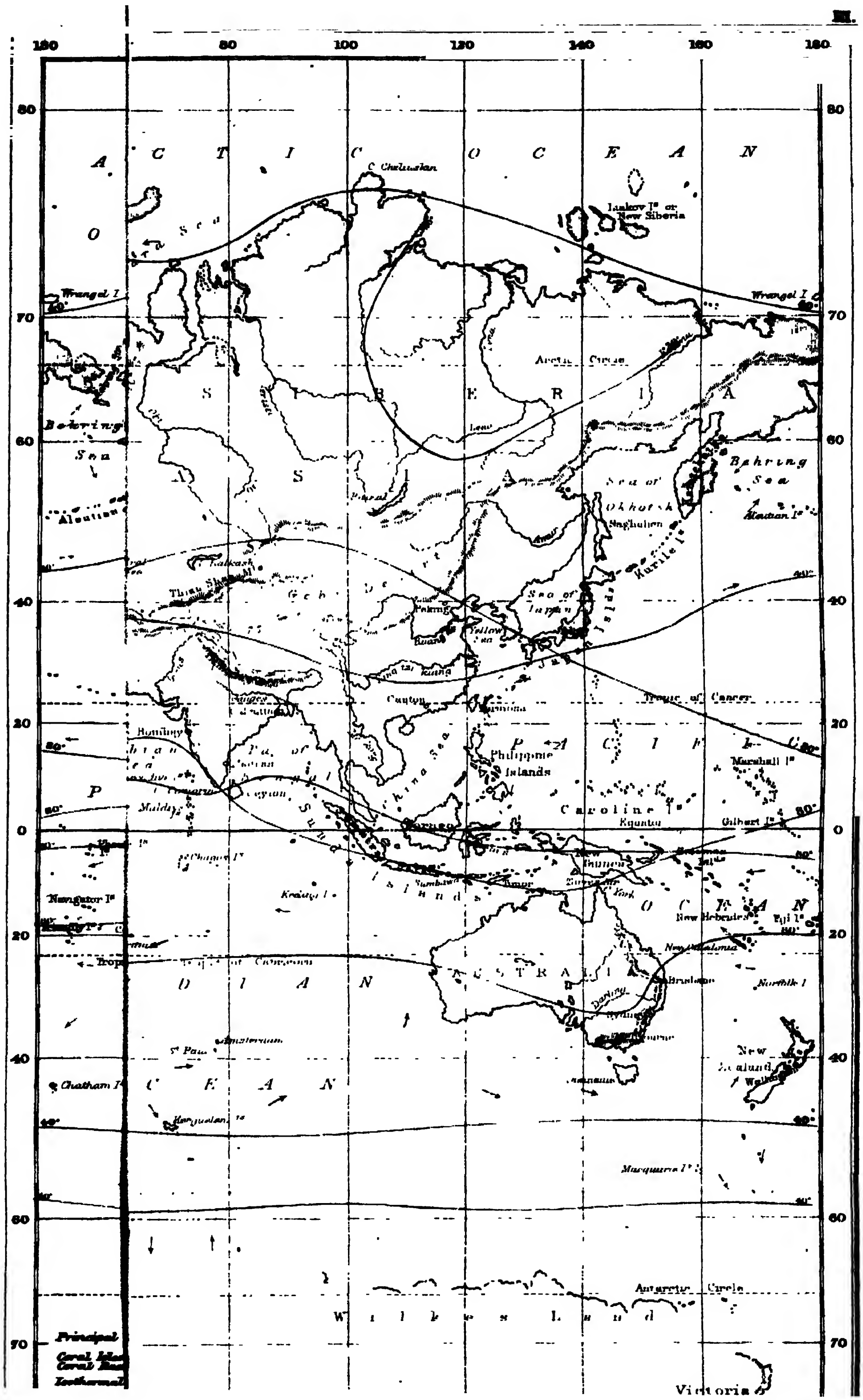
CONTINUITY OF SUBSIDENCE. CORAL ISLANDS. LIMITS OF GROWTH; CAUSED BY COLD CURRENTS AND MUDDY WATER. DARWIN'S RESEARCHES. REEF-BUILDING CORALS. ATOLLS, BARRIER REEFS, AND FRINGING REEFS. DEPTH OF SURROUNDING OCEANS. ZONE OF CORAL GROWTH. DARWIN'S HYPOTHESIS. FORMATION OF CORAL-ROCK. DANA'S DESCRIPTION OF CORAL ISLANDS AND THEIR GROWTH. EXTENT OF SUBSIDENCE. ABSENCE OF VOLCANOES. VOLCANOES EVIDENCE OF UPHEAVAL. RATE OF CORAL GROWTH. ANTIQUITY OF CORAL ISLANDS. OTHER SUGGESTED ORIGIN OF CORAL ISLANDS. OPINIONS OF L. AND A. AGASSIZ, LE CONTE, AND J. MURRAY.

Continuity of Subsidence. We have shown in the last Chapter that even within *historical* times there have been not inconsiderable changes in the level of the land in various parts of the world. But there is no evidence of any such changes having within these times exceeded 100 feet, although it is clear that both in Europe and America the same series of changes, that is to say, those which come within the life of the existing species of mollusca, etc., may be prolonged back into a far more remote antiquity.

Coral Islands[1]. There is, besides, another class of evidence, possibly a little more hypothetical, which embraces changes of much greater extent, and which, starting, as in the other instances, with changes still in progress, carries us back to possibly yet more distant times. That evidence is afforded by the coral islands which stretch almost across the Pacific nearly parallel with the Equator, namely, from Pitcairn's Island and the Low Archipelago to the Pellew Islands, a distance of about 7000 miles, with a width probably of not less than 1000 to 1500 miles. Within this area there are no fewer than 290 of these islands, besides a large number of 'barrier-reefs.' (Map, No. III.)

Another band of Coral Islands extends between India and Madagascar, of more than 1500 miles in length, and a branch of this group stretches up the Red Sea. Another cluster of coral reefs ranges from the shores of Brazil, across the West-Indian seas, to the coast of Florida. But no coral islands

[1] The reader will find in Darwin's 'Coral Reefs' and Dana's 'Corals and Coral Islands,' a very complete description of these structures.


ARCTIC OCEAN
C. Cheliuskin
Liakov Is or New Siberia
Wrangel I.
Arctic Circle
SIBERIA
Behring Sea
Aleutian Is
ASIA
Sea of Okhotsk
Saghalien
Kurile Is
Sea of Japan
Japan Islands
Peking
Yellow Sea
Tropic of Cancer
Canton
Bombay
Philippine Islands
PACIFIC
Marshall Is
Caroline Is
Equator
Gilbert Is
Maldive Is
Ceylon
China Sea
Borneo
Sunda Islands
Sumbawa
Timor
New Guinea
Navigator Is
New Hebrides
Fiji Is
New Caledonia
INDIAN OCEAN
AUSTRALIA
Brisbane
Norfolk I.
Darling
Sydney
New Zealand
Wellington
St Paul
Amsterdam
Chatham Is
Kerguelen Is
Macquarie Is
Antarctic Circle
Wilkes Land
Victoria
Principal
Coral Islands
Coral Reefs
Isothermal

exist either in the North or South Atlantic, nor along the whole range of the western coast of North and South America, nor on the southern coasts of Australia, nor on the south or west coasts of Africa.

Limits of Growth. This restricted distribution is, however, readily accounted for. It is found that reef-building corals, while they live and flourish in waters perpetually disturbed and under the most terrific surf, yet require for their existence waters perfectly clear, and not under 68°F. of temperature, so that where the water is in any degree muddy owing to the proximity of large muddy rivers, or where the great polar currents of the ocean cause an abnormal reduction of the temperature, there reef-making corals cannot exist.

Thus, the great Humboldt current, which carries the waters of the Antarctic seas up the coasts of Chili and Peru as far as the Equator, is so much below the temperature of the tropics, that even at the Galapagos Islands, under the Equator, the surface-waters have at times a temperature of not more than 58°. In the same way, another cold current comes up from the Antarctic seas, and sweeps along the coasts of south-western Africa; while another current, from the North Pacific, sweeps past Japan down to the shores of China.

It is the influence, therefore, of these agencies on the life of the polype that limits the range of coral islands and reefs to special oceanic areas. But it is not our intention to consider these islands in their natural-history point of view. We have to look at them only with reference to their bearing on two great problems in geology; namely, the changes of the relative level of land and sea, and the formation of those many limestone strata, whether of Palæozoic or of Jurassic age, the origin of which is referred to the agency of coral life.

Darwin's Researches. Darwin showed that the species of coral which build up the great reefs only live in shallow water, where the heat and light are both vivid, and where the motion and play of the waves are rapid and continuous. A depth of about fifteen fathoms seems to be the downward limit at which these animals can flourish. The great wall-sided coral islands and barriers, rising from depths of 2000 feet or more, must then have commenced their growth in shallow water, and continued it upwards at such a rate as to have always kept their living surface near to the surface of the ocean, while the rock base, on which they rested, gradually subsided beneath it. Hence, as coral islands are found rising from very deep water far from any land, Mr. Darwin drew the conclusion 'that when the corals began to build there was more land where there is now more sea, and that, since that time, a wide-spread subsidence of land and sea-bed must have taken place' (Fig. 100 represents the site of submerged land).

Reef-building Corals. For our purpose corals may be divided into two groups: *detached corals*, living at all depths and in water of almost

all temperatures; and *reef-building corals*, which latter are definitely limited in their range, both with respect to temperature and to depth.

Dana describes a region of these reef-builders as 'a plantation of living corals,' in which various species are growing together, at one place in crowded thickets, at another in scattered clumps over fields of coral sand. There is the same kind of diversity that exists in the distribution of vegetation over the land. Some of the kinds branch like trees of small size or shrubs (*Madreporæ*); others form closely-branched tufts (*Pocilliporæ*, some species of *Porites*); others resemble clustered leaves (*Merulinæ*, *Manoporæ*), or tufts of pinks (*Tubiporæ*), or subglobular forms (*Astræa*, *Mæandrinæ*, and some species of *Porites*); and others are groups of slender, brilliantly-coloured twigs (*Gorgoniæ*). When alive in the water all these corals are covered throughout with expanded polypes, emulating in beauty of form and colours the flowers of the land. Amongst them various shells live and die; and, according to Darwin, some fishes browse on the living polypes.

FIG. 100. *The Maldive Archipelago of Coral Islands or Atolls in the Indian Ocean*—(Darwin)—470 miles in length by 50 miles in average width. The dotted line shows the probable area of submerged land.

Structure of the Islands. Coral formations, while of one general mode of origin, are of three kinds; first, coral islands or atolls, which are isolated, ring-shaped islands, consisting entirely of coral; secondly, of fringing reefs, which are banks bordering mainlands and islands; thirdly, of barrier-reefs, which are reefs skirting the land, but at some distance from it.

The atolls vary in size from a few hundred yards to as much as 90 miles long, and 10 miles wide, and the average width of the annular reef may be taken at a quarter of a mile: in no instance does it exceed

half a mile. Barrier-reefs are sometimes of enormous extent; the one which fringes the north-eastern coast of Australia extends for a distance of 1200 miles, at an average distance of from 20 to 30 miles from the shore.

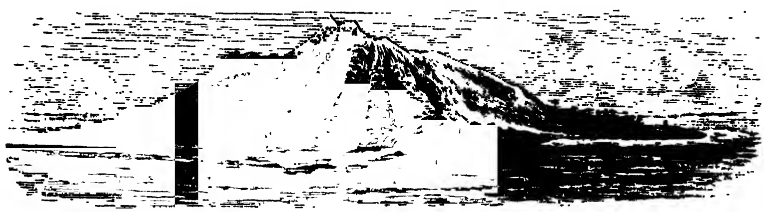


FIG. 101. *High Island with Fringing and Barrier Reefs.* (Dana.)

Surrounding Depths. In Coral-islands the outer edge of the coral-reef dips gradually for a distance of 200 to 300 yards, and then plunges at a rapid angle into great depths. Dana states that, according to Wilkes, 2 miles east of Serle's Islands no bottom was found at a depth of 600 fathoms; 1½ miles south of the larger Disappointment Island none at 550 fathoms; and a mile from the east end of Metia none at 600 fathoms. Darwin says that Captain Moresby found at a distance of only 600 feet from Diego Garcia no bottom at 150 fathoms; at 300 feet off Cardoo Atoll Island none at 200 fathoms; while at 2200 yards from Keeling Island, Admiral Fitzroy found no bottom at 1200 fathoms; but the line at a depth between 500 and 600 fathoms was partly cut, as if it had rubbed against a projecting ledge of rock.

FIG. 102. *Map of Bolabola Island with its Barrier Reef.* (Darwin.)

The great barrier-reef of Australia rises at its seaward edge, according to Jukes, from depths which certainly exceed 1800 feet; and he likens it to a great submarine wall fronting the sea, and resting at each end on shallow water, while its upper surface forms a plateau varying from 10 to 30

FIG. 103. *View from the central heights of Bolabola Island.* (Darwin.)

fathoms in depth; studded all over with steep-sided, block-like masses, which rise up to the level of low water.

FIG. 104. *Fringing or Barrier Reef of Abrolhos, Brazil.* (Dana.)

Although Darwin found that in ordinary cases reef-building polypes do not flourish at greater depths than about 15 fathoms, they may continue to live to depths of 20 or 30 fathoms. Dana limits the depth at which they live to about 100 feet. As they cannot exist at levels

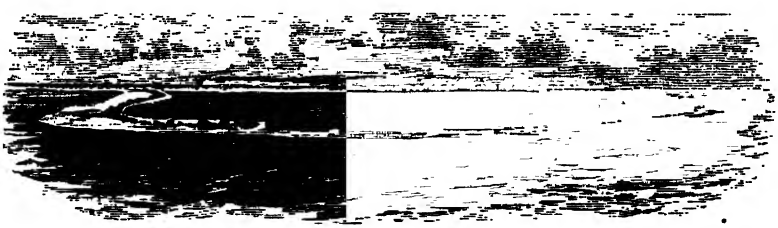


FIG. 105. *View of a Coral Island or Atoll, with central lagoon.*

FIG. 106. *Section of the Rim of an Atoll.*—Further to the left the Reef plunges rapidly. To the right is the Lagoon.

higher than extreme low water,—exposure to the sun, even for a short period, proving fatal,—it follows that a coral-reef cannot be raised above the sea-level, nor be extended to depths exceeding about 100 to 120 feet, by the unaided efforts of its builders.

When the coral-growth reaches the surface of the sea, the battering power of the waves, which are constantly breaking on its outer margin, throws up the broken coral, and raises the outside edge of the reef. Dana

says, that after the growing corals and the accumulating débris reach low-tide level, the polypes mostly die; but the waves continue to pile up on the reef sand, pebbles, and broken masses of coral,—some of the masses being two or three hundred cubic feet in size,—and a field of rough rocks begins to appear above the waves. Next, a beach is formed; and the bank of coral débris, now mostly above the salt water, becomes planted by the waves with sea-borne seeds. Trailing shrubs spring up; and afterwards, as the soil deepens, palms and other trees rise into forests, and the coral island or atoll comes forth finished.

Darwin's Hypothesis. But, if the coral polype lives only in shallow water, in what way could the coral-reefs which rise out of such great depths have been formed? Darwin answered this by showing that the production of barrier-reefs and atolls might be ascribed to a great secular subsidence of the foundations upon which they rest. Thus, if a fringing-reef surrounds an island which is gradually sinking beneath the

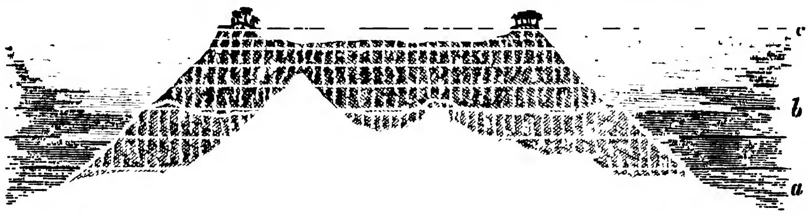


FIG. 107. *Diagram showing, according to Darwin, the mode of formation of a Coral Island.*
a. Original Island with Fringing Reef. *b.* The stage to which it continued a Barrier Reef. *c.* The finished Atoll.

sea, the upward growth of the corals will neutralise the downward movement of the land so far that the reef will appear to be stationary, whilst it is really growing upwards (Fig. 107). The island, however, as subsidence goes on, will gradually diminish in size, and a channel will, by degrees, be formed between it and the reef; so that eventually, should the depression continue, the island will be reduced to a mere peak in the centre of a lagoon (Fig. 103); and the reef, from a 'fringing-reef,' will become converted into an 'encircling barrier-reef,' with deep water all round (Fig. 101). If the subsidence be continued still further, the central peak will finally disappear altogether, and the reef will become a more or less complete ring, surrounding a central expanse of water; thus becoming converted into an atoll (Fig. 105). The production, therefore, of encircling barrier-reefs and atolls is due to a process of subsidence of the sea-bottom. At the same time, fringing-reefs are compatible with a land slowly rising, or even stationary.

Formation of Coral-rock. The interstices of the dry coral-bank, after the death of the polypes, become filled up with sand produced by the wear of the coral, and with carbonate of lime taken up and re-deposited by the rain-water percolating through the reef, which cements the whole into one solid mass. When the mass thus consolidated has been—which soon

happens—raised to some height above the sea-level, it is generally seen to be of a white colour; but in some few parts it is rendered reddish by the presence of a small quantity of ferruginous matter. It is very hard and sonorous under the hammer, and is obscurely divided by seams dipping at a small angle seaward. It consists of fragments of the corals which grew on the outer margin, some quite, and others partially rounded; some small, and others between 2 and 3 feet across; and of masses of previously formed conglomerate, torn up, rounded, and re-cemented; or it consists of a shelly grit entirely composed of rounded particles of shells, corals, the spines of Echini, and other organic bodies. The structure of the coral in this breccia has generally been much obscured by the infiltration of spathose calcareous matter. Darwin says that he collected a series, beginning with fragments of unaltered coral, and ending with others where it was impossible to discover with the naked eye any trace of organic structure. In some cases he was enabled with the aid of a lens, and by wetting the specimen, just to distinguish the boundaries of the altered coral and spathose limestone [1]. He speaks of one coral mass now forming on the shores of the Maldiva Atolls, as markedly resembling a limestone breccia from Devonshire.

Dana describes the rock forming the coral platform and other parts of the solid reef as a white limestone, made of corals and shells, and having a composition like that of ordinary limestone. In some parts it contains the corals imbedded; but in others it is perfectly compact, without a fossil of any kind, except an occasional shell. In no case is it earthy like chalk. The compact non-fossiliferous kinds are formed in the lagoons or sheltered channels; the kinds made of broken corals, on the sea-shore side, in the face of the waves; those made of corals standing as they grew, in sheltered waters where the sea has free access. The principal varieties of the coral-rocks are, according to the same authority:—

1. A fine-grained, compact, and clinking limestone, as solid and flint-like in fracture as any Silurian limestone, and with rarely a shell or fragment of coral visible.

This variety is very common; and where coral-reefs or islands have been elevated, it often makes up the mass of the rock exposed to view. The absence of visible fossils, while the rock was really made out of corals and shells, is a remarkable and instructive fact.

2. A compact oolite, consisting of rounded concretionary grains, and generally without any distinct fossils.

3. A rock equally compact and hard as No. 1, but containing imbedded fragments of corals and some shells.

4. A conglomerate of broken corals and shells, with little else, very firm and solid; many of the blocks several cubic feet in size.

5. A rock consisting of corals standing as they grew, with the interstices

[1] *Op. cit.*, pp. 13 and 154.

filled in with coral sand, shells, and fragments. In general the rock is exceedingly solid; but in some cases the interstices are but loosely filled [1].

Such is the character of these wonderful growths rising up in the midst of the great oceans, and which help so greatly to abstract from their waters the lime which, as before shown in Chapter VII, is being incessantly and largely carried down into the sea by all the rivers of the world. Here, as Dana forcibly observes, 'we may have the rocks from the snow-covered summits of the Himalayas, the limestones of the burning plains of India, and the strata of inaccessible China, removed from their respective districts in imperceptible atoms into the great common receptacle—the ocean, where, after circulating over thousands of miles and for unknown times, they are brought to light and rendered tangible again by the incessant labours of millions of minute living gelatinous bodies, and by these insignificant organisms the lime is built up again into masses almost rivalling the originals in dimension and importance, but losing in this its new dress all traces of its diverse origin and diverse age, and while re-appearing in strata, may be as solid as the older rocks, nevertheless amongst the newest of the deposits forming the land of the globe.'

Extent of Subsidence. Viewed either in the light of rock-

FIG. 108. *View of Metia, an elevated Coral Island.* (Wilkes.)
The cliffs are 200 to 300 feet high, and present the appearance of a hard limestone.

formation, or in the light of a widely spread subsidence, the phenomena are equally remarkable. If the coral islands are registers of subsidence, a vast area in the Pacific has partaken in it, measuring 6000 miles in length from east to west (a fourth of the earth's circumference), and 1000 to 2000 in breadth. Just south of this area there are some coral-reefs, and north of it are a few large coral islands; but they diminish toward the Equator, and with a few exceptions, disappear to the north of it. The smaller atolls, and the absence of the central island, indicate the greatest amount of subsidence. Darwin says that the extent of this subsidence may be inferred from the soundings near some of the islands, which extend to depths of 3000 feet or more; while, as two hundred islands have disappeared (and it is probable that some among them were at

[1] 'United-States Exploring Expedition,' 1838–42, vol. x. p. 617.

least as high as the average of existing high islands), the whole subsidence cannot be considered less than 6000 feet; and that probably this sinking began in the post-Tertiary period. He goes on to say that, since the subsidence of this area ceased—for the wooded condition of the islands is proof of its having ceased—there have been several cases of isolated elevations; as, for instance, Oahu (Sandwich Islands), 25 feet; Elizabeth Island, Paumotu Archipelago, 80 feet; Metia or Aurora, 250 feet; Atiu (Hervey Group), 12 feet; Mangaia, 300 feet; Rurutu, 150 feet; Eoa (Tonga Group), nearly 300 feet; Vavao, 100 feet; Savage Island, 100 feet; and many others.

Absence of Volcanoes. Darwin also remarks, that the absence of active volcanoes throughout the greater part of the area of subsidence, namely, in the central parts of the Indian Ocean, in the China Sea, in the sea between the barriers of Australia and New Caledonia, in the Caroline, Marshall, Gilbert, and Low Archipelagoes, is a very striking fact. So is the presence of active volcanic vents and chains on or near many of the shores which are fringed with reefs; for these fringed coasts have in a number of cases been recently upheaved.

The absence of coral islands in other areas of elevation, such as the long western coast of South America and other parts of the Pacific, where volcanic action is rife, has been already accounted for by the influence of cold polar currents; but, until it could be shown that volcanoes were absent or inactive in subsiding areas, the conclusion that their distribution depended on the nature of the subterranean movements in progress would have been hazardous. 'But now,' Darwin remarks, 'it may be considered as almost established that volcanoes are often present in the areas which have lately risen or are still rising, and are invariably absent in those which have lately subsided or are still subsiding'; and this he looked upon as the most important generalisation to which the study of coral-reefs indirectly led him.

He concluded by remarking that these great barrier-reefs and coral islands 'offer a grand and harmonious picture of the movements which the crust of the earth has undergone within a late period. We there see vast areas rising, with volcanic matter every now and then bursting forth. We see other wide spaces sinking without any volcanic outbursts; and we may feel sure that the movement has been so slow as to have allowed the corals to grow up to the surface, and so widely extended as to have buried over the broad face of the ocean every one of those mountains, above which the atolls now stand like monuments, marking the place of their burial.'

Thickness. It has been estimated that some of these reefs have a thickness of from 1000 to 2000 feet. Various attempts have been made by boring to determine this point, and ascertain the character of the rock at depths; but none have yet gone beyond 45 feet. The magnitude of their mass is, however, indicated to a certain extent in those cases where there

has been an upheaval by which the reef has been raised above the level it originally occupied. In some of the islands the coral-limestone now forms cliffs 250 to 300 feet or even more in height, and in no case has the base of the coral-growth been reached; while the precipitous submarine slopes give reason to believe that it often extends to considerable depths.

Rate of Growth. There is a great difference of opinion as to the rate of growth of the reefs. Darwin states that, while in some cases, reefs have shown but little alteration during a long course of years, there are other instances where the rate of growth in one year has been proved to be 2 to 3 feet; and he mentions a case where a channel, deep enough for a schooner to enter, was choked up in less than ten years. Dana, on the other hand, thinks that, although the rate varies considerably, it has on the whole been over-estimated; and says that it is often not more than 1 inch in the year, and sometimes even less than that. He mentions one case where a species of madrepore attained a height of 16 feet in sixty-four years, or at the rate of 3 inches in the year; and these grow with much greater rapidity than many massive corals. It is, however, to be remarked that one set of observations was chiefly made on the coast of Florida, and the others in islands of the Pacific.

Antiquity. In any case, the time taken for the building up of these enormous structures by their minute architects must be of great length. There is in fact no reason why these structures, many of which are still in progress of construction, may not have commenced their growth in some geological period. Since Darwin wrote, a much greater antiquity has been assigned to the troughs of the two great oceans than was at that time suspected, so that it is possible that the foundation of some of the many coral islands may have been laid, at all events, in some of the later, if not the earlier, Tertiary periods.

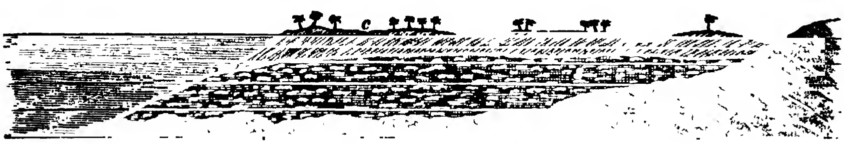


FIG. 109. *Ideal section of the Florida Coral-reef.* *s*. Shell-bank resting on Tertiary strata. *c*. Coral-reef.

Other Origin of Coral Islands. More recent observations have shown that the hypothesis of Darwin is not applicable to all coral-reefs; and that, while it explains the formation of atolls and of many coral islands, it fails to explain that of others, especially those which subtend continental areas. Louis Agassiz [1] some years ago contended that the Florida reefs in particular had distinctive characters which could not be explained by subsidence. He showed that the southern portion of the peninsula of Florida

[1] 'Mem. Mus. Comp. Zool.'

is built of successive concentric barrier-reefs, which have been gradually cemented into an extensive land tract by the accumulation and consolidation of sand and silt between the coral growths.

Professor Le Conte attributed the formation of the Florida reef, primarily, to the accumulation of a submarine bank by the action of the Gulf Stream, which bank, when it reached to within a few fathoms of the surface, served as the substructure for the growth of the coral reefs; the channels between these, being gradually filled up with débris, were converted into swamps, and then into dry land.

Alexander Agassiz, while agreeing with these general conclusions, has, from the results of later deep-sea dredging, been led to form a somewhat different opinion of the growth of the original banks, of which he has recently given some interesting details [1].

The north part of Florida consists of low hills of Vicksburg Limestone of late Eocene age. From the trend of these hills, they are supposed to have been raised during the Miocene period; southwards the limestone passes below the sea-level, forming a base on which an old coral-reef grew. A subsequent subsidence gave rise to an extended submarine plateau, directly in the track of the Gulf Stream, and on this, which was too deep for the growth of reef-corals, a great bank, formed by the accretions of the solid parts of molluscs, echinoderms, corals, crustacea, etc., which lived and died upon it, was gradually built up. When this bank reached the level at which reef-corals prosper, there coral-reefs sprang up and flourished, forming at first a fringing reef, which by degrees extended itself laterally,—the conditions favourable for the growth of coral not being caused by subsidence, but by the gradual rise of the bank itself outside the incipient reef in consequence of the accumulation of animal débris upon it. The suitable level once attained, reef-building corals spread themselves over it, and thus the great reef gradually grew *pari passu* with the extension of the shell-bank.

In the opinion of Alexander Agassiz, the Gulf Stream, which flowed over this submarine bank, only indirectly contributed to its increase, not by carrying silt and débris from the land to the westward, but by transporting from that area the abundance of food needed for the rapid and large development of molluscs and other invertebrates; for it is only under such favourable conditions of food-supply that the profusion of life found by the dredge down to the hundred-fathom line could be sustained; and, as a corollary of this, Agassiz infers that the great oceanic currents, by bringing with them a superabundant supply of food (*Foraminifera*, *Radiolaria*, etc.), form an important factor in determining the present distribution of the marine invertebrates, and that they were equally so in past geological times.

[1] 'Mem. Amer. Acad. Arts and Sciences,' vol. xi. p. 107, 1883.

As soon as a reef reaches the level of the lowest tides, it ceases to grow; for exposure to the sun, even for a very short time, is sufficient to kill the coral polype. The mass of dead coral, quickly riddled and weakened by boring molluscs, echinoderms, annelids, sponges, etc., and exposed to the action of the huge breakers which pound incessantly upon the steep face of the reef, is broken up into fragments. Some of these are thrown up by the waves above the sea-level, and go to form beaches and new land. Another portion, falling into deeper water, undergoes further wear and tear by trituration, and passes into coral-sand and silt; and this, mixed by the action of the tides and currents with the débris of the mollusca and other invertebrata, contributes to the extension and widening of the bank.

The substructure formed by this detrital matter along the coast is gradually raised to a level at which corals flourish under the continued influence of the same abundant food-supply provided by the passage of the Gulf Stream; while this powerful current at the same time scours away on the seaward side the shore sediment or silt under which the polypes would otherwise be choked and killed. The limits of depth at which reef-building corals can exist are less here than in the open ocean, not exceeding forty to fifty feet; but this limitation is shown by Agassiz to be due to the fact that, in stormy weather, the water round the reefs becomes discoloured by the fine, powdered, calcareous ooze for a considerable distance outwards, sometimes as far as ten miles. This ooze rapidly sinks to the bottom, leaving the upper water clear, but beyond a certain depth the corals are choked. The limited bathymetrical range of reef-building corals is thus further dependent in this case on local causes, whereas in the open ocean such interfering influences, if they exist, lie at greater depths.

The corals which go to form the Florida and other analogous reefs are chiefly species of *Madrepora*, *Porites*, and *Mæandrina*. There are also immense masses of millipores (*Udotea*) and corallines in the shallower parts of the reef. The exposed surface of the reef is soon overspread, and its interstices filled, by shell- and coral-sand and other débris. This becomes cemented by water holding carbonate of lime in solution and ultimately forms a layer of hard limestone, dipping slightly towards the sea. Successive outward layers of limestone have been thus formed, which with the aggregation of sand and silt in the intermediate channels have in the course of time built up the whole of the land of Southern Florida—land which has a superficial area estimated at not less than 20,000 square miles

Estimates of the age of these extensive reefs are difficult to form, and can only be rough approximations. Alex. Agassiz thinks it would probably take 1000 to 1200 years for corals of the kinds there living to rise from

the seven-fathom line to the surface; and, supposing a reef to have an average width of half a mile, and its lateral growth to be four or five times more rapid than its vertical increase, we should get not less than 20,000 years as the age of this outer portion only. But, as before mentioned, the rate of coral-growth is, as shown by Darwin and Dana, very variable.

Professor Le Conte also draws attention to another process, which must have been instrumental in adding to the land. In the great swamps that have often been formed behind the outer reefs, mangrove-trees, floated from off some of the small mangrove reef-islets, have been stranded by their long roots on the shallower silt- and sand-banks, and have there taken root and developed into forests of mangrove-trees standing in the shallow waters. Their tangled roots and branches stay the passage of the sediment carried there by streams and currents, and gradually the sand-bank, with its forest-growth, is raised above the level of the water.

Mr. John Murray[1], reasoning from the observations he made during the 'Challenger' Expedition, has expressed views very similar to these respecting the origin of the coral islands of the Pacific. He describes the ocean as swarming to a depth of 600 feet with pelagic gasteropods, pteropods, heteropods, cephalopods, fishes, etc., together with calcareous, siliceous, and other Algæ, Radiolaria, and Foraminifera. As these die, when they fall into deep water, their calcareous skeletons become, during their long downward transit, dissolved by the carbonic acid in solution in the sea-water; but not so when their remains fall on submarine banks a few hundred feet deep, where they lodge and accumulate. Some of the banks may originally have been old volcanic islands worn down by marine denudation. When these foundations are sufficiently raised by the accumulation of this shell débris the corals begin to build, and, owing to the greater supply of food on the outer sides of the bank, they there build with greater vigour. This, with the heaping up of the dead coral from the outside, and its removal in part by solution in the interior, gives rise to the atoll form with the central lagoon. Mr. Murray further thinks that the coral islands afford evidence of rest and even of elevation, but not of subsidence.

The wide extent of the Peninsula of Florida, so largely beyond that of ordinary coral islands, and the absence of central lagoons, lends support to the opinion of L. and A. Agassiz; but it is more difficult to explain the peculiar conditions of the coral islands of the Pacific on a similar hypothesis. The present Florida reef was preceded by a shallow submarine plateau and shell-bank. The great reefs of Yucatan, the Bahamas, and of the south coast of Cuba, of Brazil (Fig. 104), and possibly of Australia, have probably originated in the same way as that of Florida; but in the Pacific no extent

[1] 'Proc. Roy. Soc. Edinb.' vol. x. p. 505, 1880.

of land-area has been formed by coral agency. The islands are isolated, and their sides precipitous; and they have central lagoons of considerable depth, sometimes as much as 240 feet. These are conditions difficult of explanation on any other hypothesis but that of subsidence. There is every reason to suppose that the whole of the Florida reef is of small thickness, probably not more than forty to fifty feet; whereas besides the depth below water of the coral-rock, there are many raised islands in the Pacific with massive cliffs of coral limestone 200 to 300 feet high (Fig. 108); and even in those cases the base of the reef is rarely if ever exposed. Further, the rapid seaward slopes of the Coral islands before described seem incompatible with the angle of repose which a loose sand- and shell-bank would take in deep water.

In some of the West-Indian islands, where there has been elevation of still greater extent, such as that on the northern coast of Cuba, coral-reef deposits have been raised to the height of 1000 to 1100 feet. At San Domingo and Barbadoes, where the elevation has likewise been considerable, the coral growth is in successive terraces and not in a continuous reef. It would appear, in fact, that coral-reefs extended as freely laterally as they do vertically,—the one process taking place when the land is stationary, and the other when it is undergoing slow subsidence. Examples due to the prevalence of the former conditions during certain geological periods are to be found in the wide-spread coral-banks of the Coral-rag and other Oolitic Formations; while the latter conditions may possibly have prevailed, and assisted, in some cases, to the building up of some of the thick masses of coral-limestones during Palæozoic times. To this question we shall have to refer again in describing the Sedimentary strata. It is certainly singular, that in the more recent geological periods we have nothing analogous to the gigantic columns of coral-limestone now standing isolated in the depths of the Pacific. Were the Tertiary seas too shallow, or were the changes of level too frequent or too rapid?

CHAPTER XV.

DISTURBED AND FAULTED STRATA.

CONFORMABLE STRATIFICATION. DIP AND STRIKE OF THE STRATA. RELATION OF DIP TO DEPTH AND THICKNESS OF STRATA. UNCONFORMABLE STRATIFICATION. TRANSGRESSIVE STRATIFICATION. FAULTS: THEIR EFFECTS; THEIR FORMS; THEIR EXTENT. EFFECTS OF PRESSURE. SLICKENSIDES. LEVELLING OF SURFACE. FAULTS ACT AS WATER-DAMS. CRUMPLED AND FOLDED STRATA. ANTICLINAL AND SYNCLINAL LINES. THE AXIS OF DISTURBANCE OF THE ARDENNES. INVERTED STRATA. CURVED AND ARCHED STRATA.

Conformable Stratification. As a consequence of changes of level of the character of those just described, it will be evident to the student that, although all the sedimentary strata were deposited in *horizontal* beds, yet that they may in many cases have lost their horizontality and become tilted at various angles to the horizon. But so long as the areas affected were large and the movements uniform, layer would succeed layer, and formation would follow on formation in regular and parallel or nearly parallel planes of deposition, producing what is termed *conformable stratification*, as in the following section :—

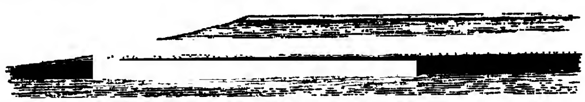


FIG. 110. *Section of Round Hill, Lansdown, near Bath (reduced one-third from section by the Geol. Survey*[1]*).* a. Great Oolite.—b. Fuller's earth.—c. Inferior Oolite.—d Marlstone.—e. Lias.—f. New Red Sandstone.

Dip and Strike. In proportion as the disturbing causes were of lesser extent and greater force, the sedimentary strata have been tilted at angles more or less inclined to the horizon, and this inclination is known as the *dip of the strata*, and the amount of it, which may extend to any number of degrees from 1° to 90°, is known as *the angle of dip*. While the inclination of the strata gives the *dip*, the course taken by the edges of the inclined strata on a plane surface, and which is necessarily at right angles to the direction of the dip, is termed the *strike* of the strata. The one serves to show the amount of displacement, which the strata at any spot have undergone, and the other, the extent and direction of the line of disturbance on the surface.

[1] The Survey sections are on an equal scale of height and distance, viz. 6 inches = 1 mile. Where the adjunct ⅔ or ½ is used, it means that the Fig. is only two-thirds or one-half the size of the original section. The base, unless mentioned otherwise, is on the sea-level. See 'Preliminary Remarks, p. iv.

In measuring the 'dip,' which is done by means of an instrument called a 'clinometer,' care should be observed to take it, whenever possible, exactly at right angles to the *strike*, or to a horizontal rectilinear line formed by the inclined strata with a plane surface. This is easily done where there is a ground-plan and section at right angles one to the other.

FIG. 111. *Diagrams showing the Strike on the ground-plan A, and the Dip in the section B.*

Relation of Dip to Depth. It often happens that it is important to know at what depth a stratum, such as a seam of coal, or a water-bearing bed, which comes to the surface at one place, *m*, is likely to be met with at another place, *n*, at a distance. One has only to measure the distance between *m* and *n*, and the angle of dip of the coal with the horizon, then as the perpendicular at *n* forms with *m n* a right angle, it is easy to determine the length of the two other sides of the triangle, the side vertical giving the depth sought. This, however, is assuming the strata to be without faults and conformable, and to dip at the same angle throughout. But in nature the dip is very rarely so uniform as to admit of geometrical methods; an allowance must be made for variations in the dip, and it is only at short distances that even these general rules can be relied on. A mean angle may, however, often be taken to obtain an approximate depth.

A dip of 45° being equal to a gradient of one in one in horizontal distance, the depth or increase of depth of the seam in a distance of 100 feet will be 100 feet; an angle of 11° representing a gradient of one in five, the depth at the same distance will be twenty feet; whilst a dip of 6° would give only a depth of ten feet. In this way, which applies to any given measure, whether it be a foot or a yard, or any other multiple—

An angle of	1°	gives a gradient of	1	foot in depth for	57	feet of surface distance.
"	2°	"	1	"	28	"
"	3°	"	1	"	19	"
"	4°	"	1	"	15	"
"	5°	"	1	"	11	"
"	6°	"	1	"	10	"
"	7°	"	1	"	8	"
"	8°	"	1	"	7	"
"	10°	"	1	"	6	"
"	11°	"	1	"	5	"
"	15°	"	1	"	4	"
"	19°	"	1	"	3	"
"	27°	"	1	"	2	"
"	45°	"	1	"	1	"

Further, supposing we wanted to know the thickness of the group of strata between *m* and *n*; the perpendicular has now to be taken at right angles to the dip, instead of to the horizon, so that the distance *m*, *n* forms the hypothenuse instead of one of the sides of the triangle. The following tables[1] may assist in such estimates, though it is to be observed, that in no case, owing to possible variations of dip and thickness, can these calculations be more than probable approximations, in proportion to the distances, to an exact determination of the depth or thickness of the strata at any particular spot. Still the student will often find it useful to know thus much.

With the horizontal distance *m n* = 100 feet.

Angle of dip.	Depth of stratum perpendicular to horizon at *n*.		Thickness of stratum perpendicular to its bedding at *n*.			Angle of dip.	Depth of stratum perpendicular to horizon at *n*.		Thickness of stratum perpendicular to its bedding at *n*.	
	ft.	in.	ft.	in.			ft.	in.	ft.	in.
1°	1	7	1	7	nearly	14°	25	2	24	2
2°	3	5	3	5	nearly	15°	26	9	25	9
3°	5	3	5	3	nearly	16°	28	7	27	6
4°	7	0	7	0	nearly	17°	30	7	29	2
5°	8	8	8	7		18°	31	8	30	9
6°	10	6	10	5		19°	34	5	32	6
7°	12	3	12	2		20°	36	6	34	2
8°	14	1	13	9		25°	46	9	42	3
9°	16	0	15	6		30°	58	0	50	0
10°	17	7	17	4		35°	70	5	57	4
11°	19	5	19	1		40°	84	2	65	6
12°	21	4	20	8		45°	100	0	70	7
13°	23	2	22	5		75°	368	0	97	0

Unconformable Stratification. When the older strata (Fig. 112, *c*) have been disturbed and thrown out of the horizontal, and newer strata (*a*, *b*) deposited over them; or where in addition, as is commonly the case, the older strata have been denuded and planed down before the deposition of the newer strata, this want of parallelism between the successive groups of strata is termed *unconformable stratification.* This *unconformity* may represent but a short break in stratigraphical succession; or it may represent a break of indefinite geological time. In the following examples we have, in one instance, strata of Mesozoic age resting on Palæozoic strata (Fig. 113), and, in the other, Cretaceous strata resting on Palæozoic strata (Fig. 112);—in the latter case, the interval of time spans the whole of the Carboniferous, Triassic, and Jurassic periods.

FIG. 112. *Section in a Quarry near Belligny, Belgium.* *a.* Chalk Marl (Marnes Nerviennes). *b.* Tourtia (Chloritic Chalk). *c.* Devonian Limestone.

[1] These tables (or parts of them) are often affixed to clinometers.

Unconformity of superposition is one of the features in stratification that it behoves the student to examine with particular care, for it marks a break in continuity, which may indicate a break, both in time and in life-forms, of an important character. It is by means also of such want of conformity at various successive periods that the relative ages of mountain-chains are determined (see Fig. 157, p. 286).

FIG. 113. *Section in a Quarry near Frome.*

A common phase of unconformity is that known as transgressive stratification or overlap, where a series of strata retain their sequence in one area, while in another they have been raised and had their edges planed down, and on these inclined edges of the older strata the upper newer beds have been deposited progressively. A well-known case of such an unconformity is that between the Oolitic and Cretaceous strata, in consequence of which the Gault, Upper Greensand, and Chalk successively pass as they range westward from Hampshire to Devonshire—from off the Lower Greensand, and over the Wealden, Oolites, and Lias, to the Trias; so that, while in the eastern area the series succeed in natural order, in the western area the Cretaceous strata rest directly on the New Red Sandstone, all the intervening Oolitic and Liassic rocks being there absent.

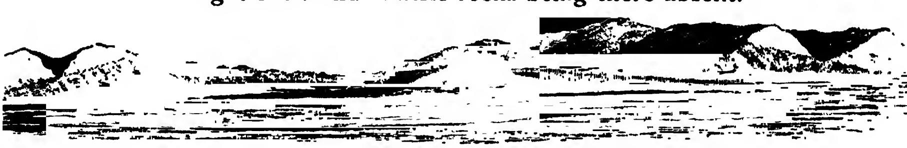


FIG. 114. *View of the Cliffs on the Dorset coast near Axmouth.* (Buckland.)
The upper light part represents the Chalk; the dotted part the Upper Greensand and Gault; the darker lower part, the New Red Sandstone. This section shows also a slight anticlinal line in the direction of the valley.

An unconformity of still more marked character brings the Chalk and Gault over the Palæozoic rocks under London. (See Pl. Sect. 4, p. 166.)

It does not, however, always follow that a break in the sequence, however well marked at one place, is apparent at another. If the older strata have not suffered much horizontal displacement or denudation at a distance from the centre of disturbance, they may retain their horizontal position, and the next series, however different in age, may then succeed in parallel and apparently conformable stratification, as in Fig. 114.

It must not be therefore assumed because of this apparent conformity that there is no break and that the strata are in regular geological sequence. As all disturbances are more or less local, some break, either in sequence or in time, may often exist where not at first suspected, and the wide gaps apparent in some areas will certainly be found filled up in others.

Faults. The strain and tension accompanying any important upheaval or displacement of some portion of the earth's crust have constantly been attended by fracture and dislocation of the strata; and the divided segments have been thrown more or less out of level, so that the two sides

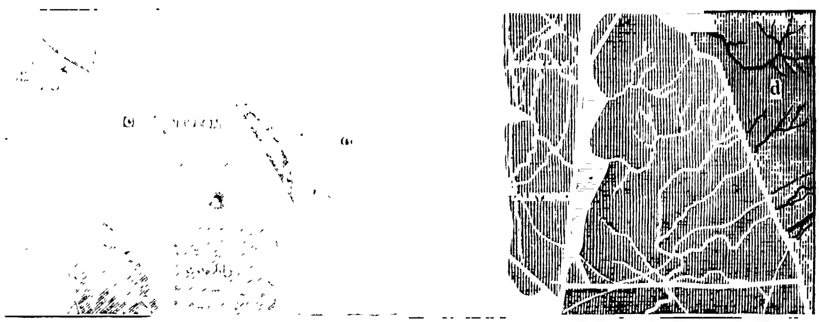


FIG. 115. *Sketch-map of part of the Manchester Coalfield.* (Geol. Mem.) *Scale, 1 inch = 3 miles.* *a.* Trias. *b.* Permian. *c.* Coal-Measures. *d, e.* Millstone-Grit and Yoredale Rocks.

do not fit, the strata being higher *on* one side than on the other. Such fractures are termed *Faults.* The thicker straight dark lines on the above map represent their course *on* the surface; while the following section shows the bearing and importance of the faults *under* the surface:—

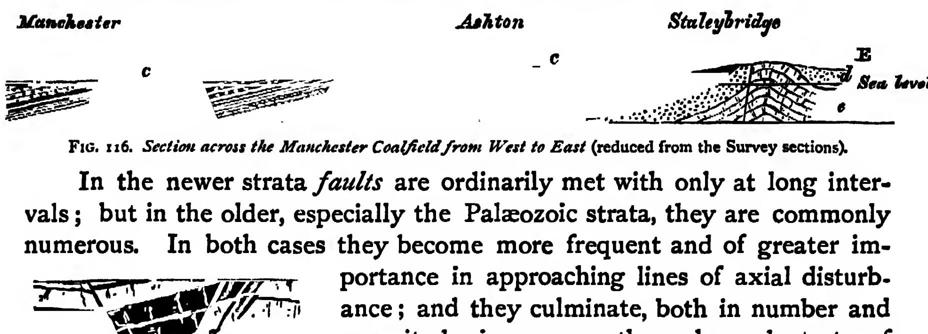


FIG. 116. *Section across the Manchester Coalfield from West to East* (reduced from the Survey sections).

In the newer strata *faults* are ordinarily met with only at long intervals; but in the older, especially the Palæozoic strata, they are commonly numerous. In both cases they become more frequent and of greater importance in approaching lines of axial disturbance; and they culminate, both in number and magnitude, in or near the upheaved strata of mountain-ranges.

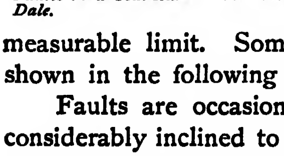


FIG. 117. *Section of a Group of small Faults in a Coal-seam in Coalbrook Dale.*

The difference of level caused by faults may vary from a few inches (Fig. 117) to many yards; while at times the scale has hardly a measurable limit. Some of the various forms and effects of faults are shown in the following sections.

Faults are occasionally nearly vertical, but more generally they are considerably inclined to the horizon, and the strata are mostly at a lower level on the upper surface of the slope or *hade*[1] of the fault than on its

[1] The miners say the *downthrow* goes with the *hade.*

under surface, although there are exceptions to this rule, as in Fig. 119, in what is known as 'reversed' faults.

Sometimes the strata maintain the same gradient or inclination on either side of a fault, but more generally they rise to the *upthrow* and dip towards the *downthrow* sides of the fault, as in Fig. 118, an arrangement which indicates to the coal-miner the direction upwards or downwards in which to seek for the displaced seams of coal, when, as so commonly happens, the strata are faulted. In other cases greater complications ensue[1].

FIG. 118. *Section on the Railway one mile S. of Tunbridge. The Hastings Sandstones are here brought up against the Weald Clay.*

While small faults are numerous, others occur, as for example in the Coal-measures, where they can be readily and surely measured, which have *throws* of many hundreds or even thousands of feet. Fig. 120 shows the 'thick coal' thrown out by a fault to the extent of about 300 feet, while the larger or Boundary Fault in the centre, which brings up the Silurian strata, *g*, into contact with the Permian strata, *b*, cannot have a throw of less than 1500 or 2000 feet. The Trias, *a*, is also here brought on a level with the Permian, *b*.

FIG. 119. *Reversed Fault in the Lower Tertiary Strata of Lewisham.* (De la Condamine MS.) *a.* London Clay. *a'.* Basement Pebble-bed. *b.* Sands of the Woolwich Series. The faults, which dip at right angles of 25° and 40°, have only a small throw of 2 to 3 feet.

FIG. 120. *Section across the great West Boundary Fault of the Staffordshire Coalfield* (Geol. Surv. reduced one-third). *a.* New Red Sandstone. *b.* Permian Red Marls, etc. *c.* Coal Measures. *g.* Silurian Strata.

In the coalfield of Wigan there are faults which measure from 400 to 1800 feet. In the Manchester coalfield there are some which are supposed to have a throw of 2000 to 3000 feet or more (Fig. 116). The Pennine chain of Yorkshire is skirted on the west by a fault which brings the Silurian strata in contact with Coal-measures, with a throw estimated at about 4000 feet; and this vast dislocation has been traced for a distance of more than fifty miles. In mountain-ranges there are faults far exceeding the

[1] See an article on various effects of faulting by Mr. Goodchild, in Geol. Mag. for May, 1883.

above in dimensions. In the Pyrenees there are some, running parallel with the axis of disturbance, that are supposed by M. Magnan to have a *throw* of many thousand mètres; and Prof. Clarence King has described two grand faults in the Great Basin, one of which forms an abrupt wall, facing east, 300 miles long, and causes a drop in Nevada County of 3000 to 10,000 feet. These faults date from about the close of the Eocene period.

Sometimes the walls of the faults are in close contact. At other times, especially if the disjointed strata are of variable hardness and resistance, the walls do not fit, and there are irregular spaces left between them,

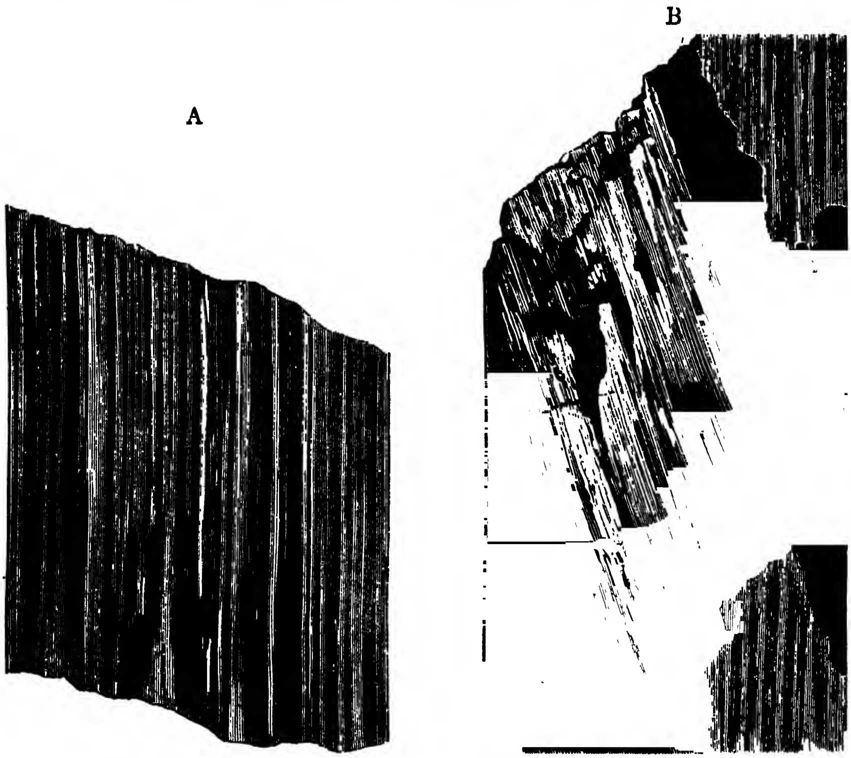


FIG. 121. *Slickenside Surfaces*, nat. size.
A represents an ordinary slickenside in Oolitic strata. *B* represents a faulted surface in which there has been successive movements in different directions.

which are filled with angular fragments and fine débris of the fractured strata and sometimes with deposited mineral matter (see Mineral Veins, Chapter XVIII). The distance between the walls of a fault, therefore, varies from nought to several feet, and even yards.

The walls of a fault are commonly ground smooth, or grooved, and often polished, the striæ following the throw or shift of the fault, which is not always in the direction of its dip. The ground surfaces, which are called *Slickensides* (Fig. 121), are sometimes as smooth and bright as though they

had received a glaze. They are not always confined to the walls of the faults, but likewise occur on other divisional planes running through the compacted rubble of the fault, in lines parallel with the including walls, showing that the fault may have shifted more than once after the first fracture (B, Fig. 121).

Faults generally run in lines more or less straight, though they are sometimes deflected, and sometimes cut off by other faults. Coal-mining affords exceptional opportunities of tracing these disturbances where the surface affords no indication of them. They often begin by a simple fracture in the strata; a slight difference of level is soon apparent, which rapidly increases and continues until the fault joins a larger one. In one instance a fault, followed from its commencement, was found in the distance of a mile to have acquired a throw of about 100 feet[1]. Sometimes a fault will die out at each end. I have known a fault of this description about half a mile long, which had midway in its course a *throw* of 30 feet. Sometimes a series of such faults will run in parallel lines, one commencing as another dies out. Others again split into lesser faults and die out. The main faults are also subject to considerable variation of 'throw.' One fault in the Coalbrook Dale coalfield has a throw at each end, to which it has been traced, of about 300 feet, while in the intermediate distance of six miles it has at one place a throw of 500 feet, at another of 450, which then lessens to 350, and again increases to nearly 700 feet.

The accompanying plan of a colliery lying between two main faults, in the same coal-field, will give some idea of the multiplicity and effects of faults above three feet of vertical disturbance in about two square miles of ground.

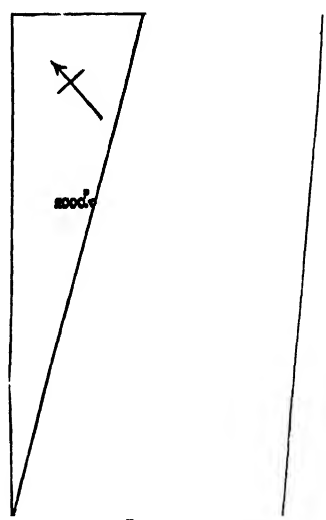


FIG. 122. *Plan of part of New Hadley Colliery. The figures give the difference of level in feet on the downthrow side. The unshaded ground is Permian.* 3 *inches* = 2 *miles.*

Faults are of very variable lengths. While many have been followed for a few miles, some have been traced for 50 or even 100 miles; and in mountain ranges there are instances where they have been estimated to have a length of 200 miles or more.

The features of the surface rarely, however, give any clue to the vast displacements underground. Sometimes they are covered by newer and undisturbed strata; by Triassic and Jurassic rocks in Somersetshire (Fig.

[1] The author 'On the Geology of Coalbrook Dale'; 'Trans. Geol. Soc. of London,' 2nd ser. vol. v. 1840, p. 455.

125), and by Cretaceous and Tertiary strata in Belgium and Westphalia (see sect. of Coal-fields, p. 260). But, even where not hidden by newer formations, the faulted strata have been so levelled and planed down by denuding agencies that rarely can even the most marvellous underground disturbances be detected by any surface-features (see Figs. 116, 120), unless it happens that there is some marked dissimilarity of colour or character in the strata brought into juxtaposition by the fault, or that the rocks on one side are so much harder than on the other as to have resisted denudation in different degrees. Otherwise it is very remarkable how all traces of the original inequalities have been removed.

This levelling of a faulted surface has taken place in many geological periods, for old faulted and disturbed areas are constantly found planed down and levelled before the deposition over them of newer strata, as in the sections above referred to. At other times the faulting has taken place after both large denudation of the older strata and the subsequent deposition of newer strata, as in the following section:—

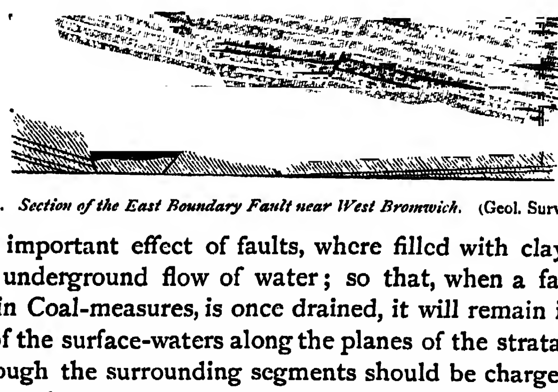


FIG. 123. *Section of the East Boundary Fault near West Bromwich.* (Geol. Survey, reduced one-third.)

One important effect of faults, where filled with clay and rubble, is to stay the underground flow of water; so that, when a faulted segment, for instance in Coal-measures, is once drained, it will remain inaccessible to the descent of the surface-waters along the planes of the strata, and may be kept dry, although the surrounding segments should be charged with water. In some cases where there has been little pressure, or where the fault-rubble is not compact, instead of protecting they are found to serve as conduits for the underground waters.

In certain cases where cavities have been left between the walls of a fault, or between the interstices of the rubble, they have been filled by the deposition of mineral matter, thus giving rise to a lode or mineral vein. Mineral veins are therefore, on one hand, closely related to *faults*; but, on the other hand, they are also related to joints and to open fissures of a character very different to that of ordinary *faults*—fissures which have at times been filled with deposited mineral matter, and at others by injected igneous-rock matter. I think it therefore better to take the subject of this class of *faults* after that of fissures and dykes (see Chapter XVIII).

Effects of Pressure. Not only are the two walls of a fault generally closely pressed against each other, but there are many cases

where the disjointed strata are strongly curved and twisted against the sides of the fault, indicating pressure of great intensity.

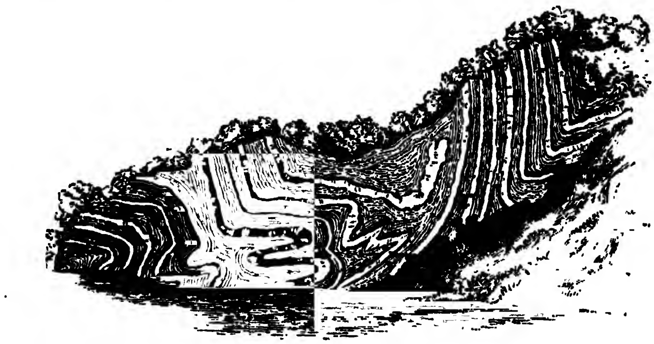


FIG. 124. *Curved and contorted Lower Carboniferous Strata lying between two Faults, Badger's Clough, near Leek.* (Geol. Survey Mem.)

In some instances the lateral pressure has even had the effect of shifting and pushing back large segments of strata one over the other, as in the following singular example (Fig. 125), which would be difficult to realise had it not been proved by actual coal-pit workings. The horizontal displacement, which extends over a length of 2 or 3 miles,

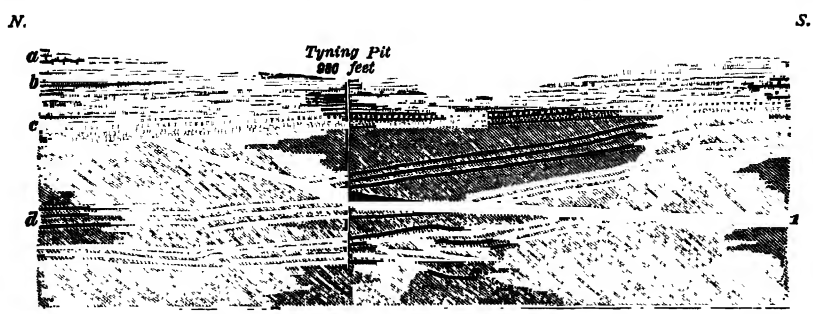


FIG. 125. *Great Slide or Overlap Fault in the Radstock Coalfield, on the north side of the Mendips.* (McMurtrie.)
1. Overlap fault: a thick loose and friable layer of crushed rock of every kind lies between the smooth and polished upper and lower surfaces of the fault; the ends of the strata above are bent downwards, while those beneath turn upwards; 2, 3, 6. Upthrow faults respectively of 18, 12 and 50 feet; 4, 5. Small Overlap faults of 18 and 30 feet.
a. Inferior Oolite; *b.* Lias; *c.* New Red Sandstone; *d.* Coal Measures.

varies from 300 to 500 feet, and the vertical throw from 105 to 316 feet (see Sect. 1, p. 260). This shows a violence of thrust and a force analogous to those met with in mountain ranges, where such faults seem, according to Heim's ingenious explanation, to be the culminating effect of the great convolutions of the strata produced by excessive lateral pressure (see Alpine Sections, p. 304).

Disturbed and Folded Strata. Not only have the sedimentary strata been tilted from their horizontal position, and faulted and shifted during their upheaval or subsidence, but this excessive lateral pressure has,

along certain lines of disturbance, crumpled, contorted, and folded whole 'massifs' in the most extraordinary manner. Crystalline and schistose rocks have been so intimately affected that the fine twisting of the laminæ is readily exhibited in hand-specimens (Fig. 126).

The flexures and folding, nearly universal in the Archæan rocks, are common in the Cambrian, and continue more or less frequent through the Palæozoic series. They are rare in the Secondary rocks, and still rarer in the Tertiary series, excepting immediately along great axial lines of disturbances.

FIG. 126. *Crumpled and faulted Schist; nat. size; the Alps.* (Heim.)

Anticlinal Ridges and Synclinal Troughs. The effects of the pressure where accompanied by upheaval has also been to raise the strata in great parallel folds and ridges of various magnitudes. The ridges formed by the crown of the folds are called *anticlinals* or *anticlines;* or taking them in their length (line of strike), *anticlinal lines;* and the troughs between them *synclinal lines* (Fig. 128).

We have examples of such anticlinals on a small scale in the short Silurian ridge of the Staffordshire Coalfield, Fig. 127, and in the axis of the Mendips (Sect. 1, p. 260) and other ranges.

But the finest exhibition of this structure must be sought in the great mountain-chains of the world, which usually consist of a parallel series of such flexures. The Alps offer a grand example. Fig. 141, p. 267, is a section of the central anticlinal axis of Mont Blanc, flanked by the synclinal troughs of Chamouni and Val Ferret, while again beyond these rise the anticlinals of Mont Brevent and Courmayeur. The full

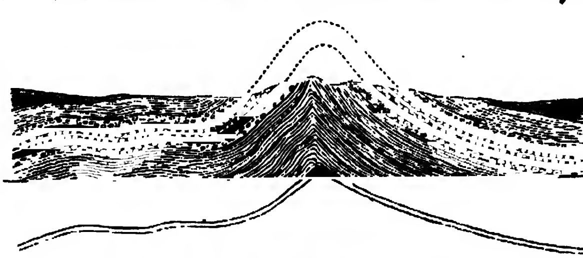


FIG. 127. *Section across the anticline of Dudley Castle Hill.* (Geol. Surv. Sect.)

series of these great folds will be found in the general section of the Alps, Sect. 3, p. 304.

Often the folds and anticlines become more acute, are brought nearer to one another, and finally doubled up and crushed together, as in the instance of the Coal-measures of Liége, Mons, and Valenciennes on the flanks of the Ardennes (p. 260, Sect. 2). In the main axis itself the older Devonian and Silurian rocks have been crumpled and compressed into a succession of continuous folds; and, as the strata have been largely denuded, they show, in a transverse section, a series of beds squeezed together and dipping generally in a similar (monoclinal) direction. This repetition of the same group of strata having the same dip (see Fig. 128) over wide districts may lead to erroneous estimates of their thickness, and is a point to be carefully regarded by the student.

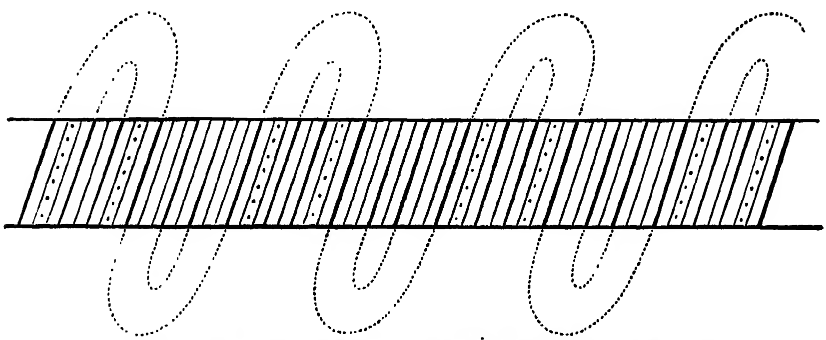


FIG. 128. *Diagram of the continuous uniform dip produced by a succession of folds.*

Excellent examples of curved strata are to be seen on the coasts of North Devon, and of Berwickshire, where the Palæozoic rocks are greatly compressed and crumpled (Fig. 129).

FIG. 129. *Section of disturbed Palæozoic strata on the Berwickshire Coast.* (Geol. Survey of Scotland.)

The extent to which the strata have in these cases been compressed has been variously estimated. The Coal-measures of the Liége coal-field may have occupied, before compression, a width almost twice as great as that which they now occupy. The Ardennes possibly occupied more than twice their present width, which is about 25 to 30 miles. M. Heim has estimated that the strata forming the Alps have lost 72 miles of their breadth (now about 130 miles) by the effects of upheaval and compression; and Prof. Claypole estimates that in the Appalachian range 153 miles have been compressed into a width of 65 miles.

This range of the axis of the Ardennes, which will be more fully described in Chapter XVII, forms one of the most remarkable lines of disturbance in Europe. It extends from the south of Ireland to the north of

Germany, and as it is flanked throughout its length (where exposed on the surface) by Coal-fields, its structure is known with a certainty rarely attainable. It would appear that the disturbance reached its greatest intensity in Belgium and the north of France, where the strata are crushed, distorted, and faulted in the most singular manner; while, at the extreme east and west points, the compression and faulting are considerably less.

This is shown by the three sections in the accompanying Plate, in which it will be noticed that the acute flexures and the extraordinary faulting and inversions of the strata, in the Carboniferous and Devonian Series of the Liége, Mons, Valenciennes, and Hardingen Coal-fields, give way in Somerset and Westphalia to more open rolls and folds. In many instances, owing to the powerful pressure, the Coal-measures have, in parts of the French and Belgian areas, been thrust (and the Coal won) *under* not only Carboniferous, but also *under* Devonian limestones.

In these sections the scale is so small that the faults, with one exception, cannot be shown, and the general features only are given.

Flexured and Inverted Strata. These effects attain their maximum development in mountain ranges, where colossal folds or flexures and inversions are ordinary features, and the complications are still further increased by the presence of enormous faults. In consequence of these disturbances, it is of common occurrence in the Alps and other mountain chains for the strata to be found in a reversed position—the newer underlying the older strata[1]. Two examples of those wonderful inversions by which in one case Secondary Strata are made to overlie Tertiary Strata, and in the other Crystalline Schists have been thrown over and above strata of Triassic and Jurassic age, will be found in Sect. 2, p. 304.

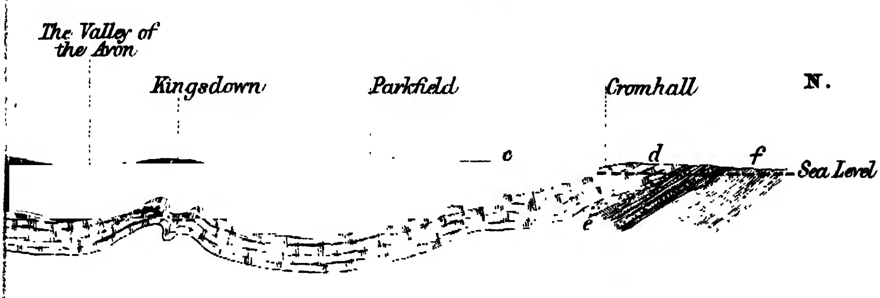
The figures (130, 131) here given show the innumerable folds and flexures

FIG. 130. *Sketch of the Stock-Pintga from Val Rusein, by Escher von der Linth.* (Heim.)
d. Brown Jura or Lias. *e.* Triassic dolomite. *f.* Carboniferous strata.

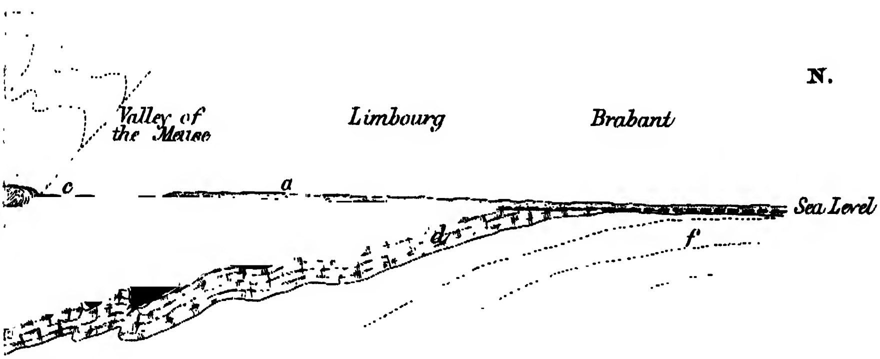
to which the great mass of the stratified rocks of the Alps are ordinarily subject, and which introduce complications of the most difficult character, bringing in the same rock at different levels, and isolating many jammed

[1] The works of Alphonse Favre and of A. von Heim, and the posthumous work of Escher von der Linth, contain admirable sketches and sections illustrative of Alpine structure.

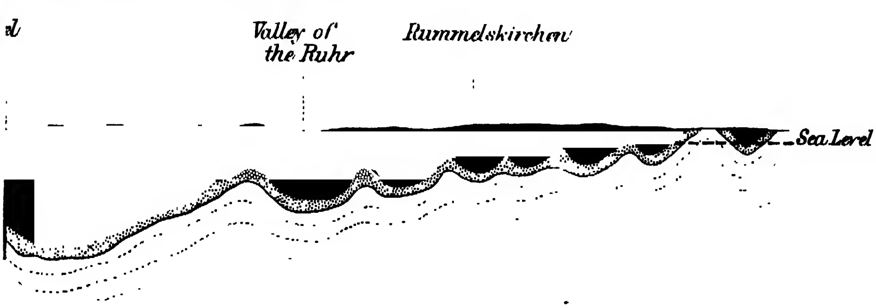
SOMERSET AND BRISTOL. LENGTH 30 MILES.



THE COALFIELD OF LIÉGE.



IE COALFIELD OF WESTPHALIA.



d Triassic Strata | c Coal Measures
ndstone | f Devonian; Silurian, and Cambrian Rocks

basal remnants of folded strata in the most unexpected positions—sometimes on the top, and at others on the sides of the mountain.

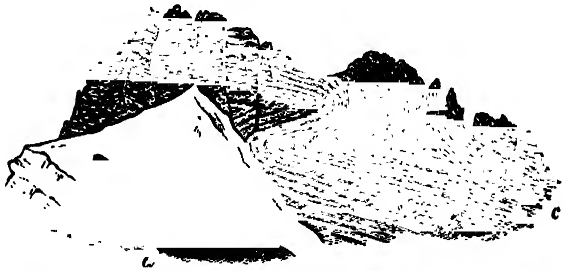


FIG. 131. *Sketch on the Eastern side of the Wingalle, by Escher von der Linth.* (Heim.)
c, Upper Jura. *d*, Brown Jura.

Such flexures as these and the colossal curves as represented in Fig. 132, formed by masses of comparatively rigid rocks, from 20,000 or

FIG. 132. *Arched Strata on the Rothenbühl—Farenboden.* (Escher von der Linth.)
a, Gault and Upper Cretaceous Strata (Senonian). *b*, Upper Neocomian (Urgonian).
c, Lower Neocomian (Valangian).

40,000 feet thick, could not take place without rending the strata to a depth proportionate to the acuteness of the flexure and the rigidity of the rocks.

It therefore constantly happens that in mountain ranges the crown of the arch, rent and fissured, has formed lines of least resistance, which have yielded more readily to denuding agencies than the less fractured synclinal troughs, remnants of which not unfrequently form mountain summits, as in Figs. 130 and 134.

The character of the great curves and foldings of the strata in mountain ranges is however best shown in the larger Alpine sections given at p. 304 of the Chapter on Mountain Ranges. I would here merely observe that with curves and folds of such magnitude and frequency it is a physical impossibility that the strata should have remained unbroken and unfissured. the deep rents and wide fissures so formed have originated the future gorges, ravines, and valleys of the great mountain ranges. Denudation must have vastly enlarged and deepened them, but it was these channels which gave the denuding agencies their grip and direction, although the original rent may be lost and disguised by the magnitude of the later operations.

CHAPTER XVI.

CLEAVAGE AND JOINTS.

SLATY CLEAVAGE. PRODUCED BY PRESSURE. EXPERIMENTAL PROOFS. CHANGE OF DIMENSIONS. DISTORTION OF FOSSILS. UNIFORMITY OF STRIKE. FAN-SHAPED ARRANGEMENT IN MOUNTAIN CHAINS. ELECTRICAL ACTION. FOLIATION OF SCHISTOSE ROCKS. JOINTS. TWO OR THREE SETS. THEIR DIRECTION IN SEDIMENTARY STRATA. 'CLEAT' IN COAL. TABLE OF ANGLES. WATER-COURSES. SYMMETRICAL FORMS OF ROCKS. JOINTS IN CRYSTALLINE AND IGNEOUS ROCKS AND THEIR ANGLES. ORIGIN OF JOINTED STRUCTURE. SMOOTHNESS OF JOINTING. REGULARITY OF FORM. UNIFORMITY OF ANGLES. COLUMNAR STRUCTURE, AND 'BALL- AND SOCKET' JOINTS. JOINTS A CONDITION OF CRYSTALLISATION. AGE OF JOINTS. IMPORTANCE OF JOINTS.

Slaty Cleavage. Slaty cleavage is that system of close parallel planes of fracture or splitting which renders rocks capable of almost indefinite subdivision in one direction, and traverses their mass generally with a dip more or less vertical, and at all angles to the planes of bedding. The cleavage planes further maintain an exact parallelism and strike over wide areas in spite of the undulations and contortions of the strata. This structure is entirely distinct from the foliation of schistose rocks, which is an induced lamination connected with metamorphism and with other causes hereafter to be considered. The complex and variable development of these several systems of planes is frequently a cause of considerable difficulty in distinguishing between foliation, cleavage, jointing, lamination, and bedding; and cases will now and then come before the student which will require his utmost caution in deciding on their relative claims. The above (Fig. 133) is an instance of cleavage in its more simple form.

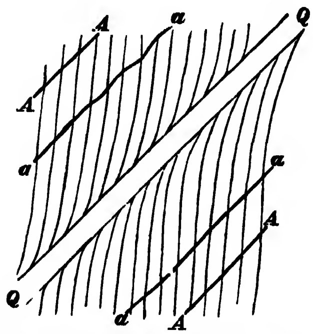


FIG. 133. *Section of the Slate Rock in the Patterdale Quarries.* (Sharpe.) *A A, a a.* Surfaces of different beds of slate dipping 45° N. The upright lines represent the cleavage planes dipping 85° N.N.W. *QQ* Vein of quartz about an inch thick. The cleavage does not pass into the quartz, and the cleavage planes curve up and down to it.

Sedgwick[1] in 1835 and Phillips[2] in 1843 showed that the direction of the cleavage-planes of the slates in the north of England and Wales

[1] See Sedgwick 'On the Structure of large Mineral Masses;' 'Trans. Geol. Soc.,' 2nd ser., vol. ii. p. 309, and vol. iii. p. 461.

[2] 'Report of Brit. Assoc.,' 1843, p. 61.

is nearly coincident with the strike of the beds and with the main direction of the mountain axes; and Darwin noticed the same fact in South America, where he found the cleavage-planes ranging over wide areas with

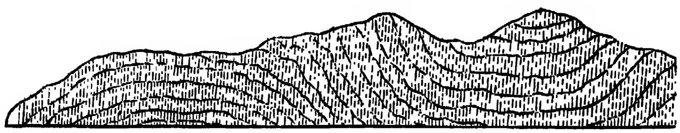


FIG. 134. *Section on the banks of the Tovey cleavage passing through curved Strata.* (Sedgwick.)

remarkable uniformity and parallel to the main axes of elevation of the Andes. It was also observed that the cleavage passed, in parallel planes, through the highly contorted and flexured strata in Wales and Cumberland independently of all the disturbances of stratification (Fig. 134).

The finer grained the rock, the finer generally the cleavage. It is the finer shales and clays of the Palæozoic strata that have, in consequence of this alteration in their structure, been converted into slate rocks, though cleavage affects the other strata, but in a degree proportionally less as they are coarser. When fine-grained rocks alternate with coarser rocks, cleavage may be slight or altogether absent in the latter, though continued through successive beds of the former. Crystalline structure also interferes with cleavage. Slight cleavage, however, exists in some of the Devonian limestones of Devonshire; as it does also in some beds of the Carboniferous rocks of Cork, but it does not pass into the overlying sandstones. Professor Harkness considered the cleavage was in some way dependent on the proportion of alumina in the rocks subjected to cleaving pressure, but this merely means that the more argillaceous, and therefore finer grained, the strata, the more subject they have been to the influence of pressure.

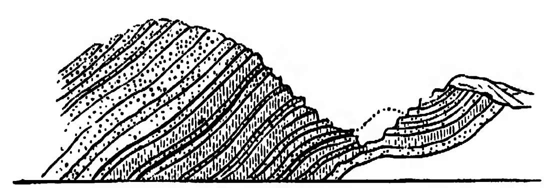


FIG. 135. *Section of the Cambrian Slates and Grits, Penrhyn.* (Ramsay.)

A good instance of the alternation of cleaved and uncleaved strata on a large scale occurs in the great slate quarries of Penrhyn, described in his 'Geology of North Wales' by Sir Andrew Ramsay, where the fine cleavage of the several beds of slate is lost in the intercalated beds of uncleaved grit (Fig. 135).

Change caused by Pressure. The observations of previous writers were confirmed by Mr. D. Sharpe[1] in 1846; who further showed that cleavage, which had previously been generally considered to be due to some form of crystalline or electrical action, was due to causes solely

[1] 'Quart. Journ. Geol. Soc.,' vol. iii. p. 74.

mechanical. He found everywhere that the direction of the cleavage-planes was at right angles to the movement of the elevatory force, and concluded that it arose from the compression of the mass in a direction perpendicular to the cleavage. This compression is shown by the distortion of the included organic remains, as well as by the flattening, in certain slaty breccias, of the included fragments, the flattest sides being always parallel to the cleavage-planes. In Fig. 136 a bed of sandy slate lying between finer slates has yielded less to cleavage than the enclosing beds, but on the other hand, is more contorted, and is pressed out in the same direction as the cleavage. Even in roofing-slates, with the assistance of a lens, the fine constituent particles are seen to be flattest between the cleavage-planes and longest along the dip of the cleavage.

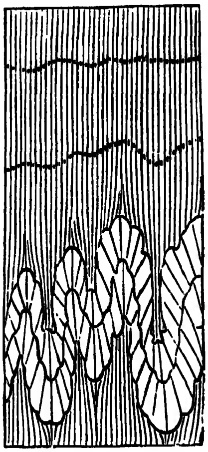


FIG. 136. *Section of a slaty rock in the Cliffs near Ilfracombe.* (Sorby.)

Sorby considers that this elongation is in most cases owing to the readjustment of the fragments in the direction of their longer axes rather than to compression of their substance, though he gives instances of the latter. He found, for example, that, when scales of iron-oxide were mixed with pipe-clay so as to have a uniform structure, and this clay was subjected to compression, the scales changed their position and arranged themselves with their longer axes at right angles to the direction of the pressure. He showed that the change of molecular arrangement existed in some limestones in which crystalline granules of very unsymmetrical character had their axes very much longer in the planes of cleavage than perpendicular to it. In a section of some Devonian limestones, unaltered by cleavage, he found encrinite joints without arrangement (*a*, Fig. 137), but when there was cleavage the joints were compressed with their longer axes in the planes of cleavage (*b*, Fig. 137).

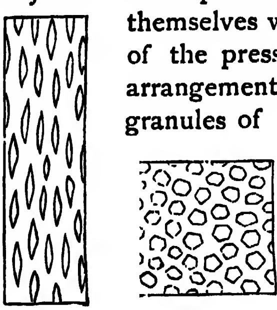


FIG. 137. *Encrinite Joints in Devonian limestone* (Sorby.)

A still more remarkable effect of cleavage-action is the occasional change of position, or of shape, of pebbles lying in slaty beds, which has resulted from the same pressure that has effected the general cleavage. In the following section the pebbles which must originally have lain with their flat sides parallel with the lines of bedding have either been shifted mechanically or else so distorted substantially by the intense pressure as to have become rearranged and elongated at right angles to the com-

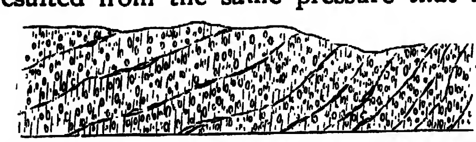


FIG. 138. *Section of a Silurian conglomerate with the pebbles elongated in the lines of cleavage; near Llanberis.* (Ramsay.)

pressing force, and obliquely to the planes of bedding. We shall have occasion to refer to this again in the Chapters on Metamorphism.

As there are scarcely any rocks whose particles are not unequi-axed, Sorby considers that, other circumstances being the same, those have the best cleavage that are composed of particles whose length and thickness differ most. The Penrhyn slates contain half their bulk of mica, in plates, $\frac{1}{2000}$ of an inch long and $\frac{1}{6000}$ of an inch thick, and it is easy to conceive how the arrangement of these microscopic particles in lines of least resistance would tend to promote cleavage; but he does not consider the presence of mica to be essential[1].

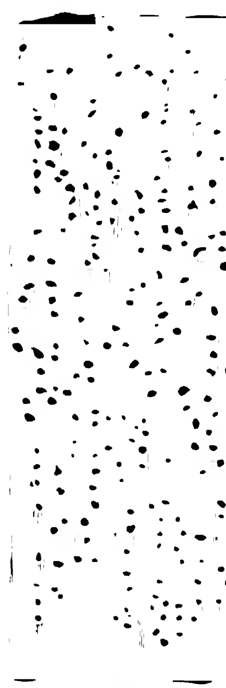


FIG. 139. *Crushed mixture of Clay and Mica after crushing.* (Daubrée.)

Experimental Proofs. Tyndall has further proved experimentally, that even in bodies of a very homogeneous character, such as pure white wax, white lead, and graphite, cleavage as clean and perfect as in any slates can be obtained by pressure alone[2]. In these cases the air-spaces and water-bubbles are lengthened at right angles to the direction of pressure.

M. Daubrée likewise has shown[3] that stearine subjected to great pressure becomes laminated. It is the same with iron under the action of a rolling mill. Prisms of lead—the one enclosing a belemnite and the other a portion of the shell of a crayfish, and subjected to a pressure of about 50,000 kilogrammes—were rendered fissile, the former being drawn out in separated segments, as in the case of the belemnites in Alpine schists, while the latter was deformed in imitation of trilobites in slate rocks. M. Daubrée also had some experiments made to show that moist clay mixed with mica and subjected to hydraulic pressure by being forced through cylinders or rectangular prisms, acquired a perfect schistose structure; the latter experiments were, however, affected by the clay having to pass through smaller apertures as well as by pressure (Fig.

Change of Dimensions. Rocks in which cleavage is present have undergone a change in their dimensions. The line of greatest elongation extends in the direction of the cleavage, and along planes of movement

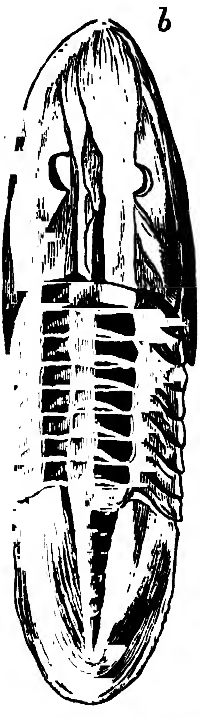
[1] 'Phil. Mag. for January,' 1856; and 'Quart. Journ. Geol. Soc.,' vol. xxxvi. p. 42.
[2] 'Phil. Mag.' for July, 1856, p. 44.
[3] 'Géologie Expérimentale,' vol. i. pp. 410–426.

perpendicular to the direction of greatest compression. The relation between compression and elongation varies in different rocks, the variation being in accordance with differences in their composition. It has been computed that in the slates of Penrhyn the absolute compression has been to reduce a width of 100 to one of 43, or to about one-half of their original volume [1].

The relative change of dimensions produced by cleavage, as shown in the distortion of fossils, varies with the angle between the planes of cleavage and bedding, being greatest where the angle is great, and least where the angle is little. Dr. Haughton [2] found that the relative compression in the following rocks, estimated by the distortion of certain fossils, is as under:—

The Green Grits of Llanberis (*Orthis expansa*)	1·881.
The Slates of Petherwin (*Spirifer disjunctus, etc.*)	3·889.
The Lingula-Flags of Pembrokeshire (*Lingula Phillipsii, etc.*)	6·881.
The Black Slates of Garth (*Ogygia scutatrix*)	11·105.

The relative effects of compression in these cases extends from two to eleven times the normal, but the absolute compression is not ascertained. There would appear also to be a sort of a sliding along the surface-planes of cleavage [3].



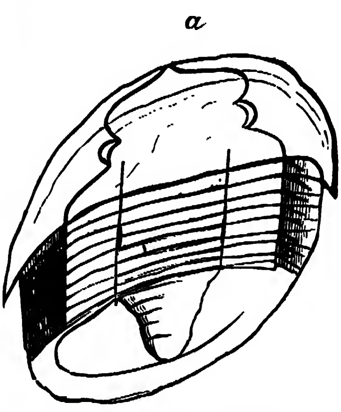


FIG. 140. *Trilobite (Asaphus Homfrayi) distorted by Cleavage*; a. compressed; b. elongated; nat. size. (Ramsay.)

This contraction of the fossil in a direction perpendicular to the line of strike of the cleavage, and its elongation in the direction of the dip of the cleavage-planes, is a further proof of a compression of the mass in a direction perpendicular to the planes of cleavage, and an expansion and shifting of the planes in the direction of the dip of the cleavage. In Fig. 140 are two examples of this distortion common with Trilobites in slate rocks.

Uniformity of Strike. The distances to which cleavage-planes strike uniformly in the same direction are very remarkable Over a large portion of Wales the direction is between N.N.E. and E.N.E., except in a

[1] Sorby, 'Edinb. New Phil. Mag.' for July, 1853.

[2] 'Phil. Mag.' for Dec. 1856, p. 409.

[3] Since these pages were written, the Rev. Osmond Fisher has more fully investigated Faulting, Jointing, and Cleavage from a mathematical point of view in the 'Geol. Mag.,' for May and June, 1884, and April 1885. He concludes cleavage as the result of 'a pressure combined with a *shear*.'

few places where it has been modified by local causes. Thus, for example, in the following districts the strike of cleavage is[1] :—

West and East of the Snowdon Anticlinal	E. 45° N.
East of the Caernarvonshire Synclinal	E. 45° N.
Neighbourhood of Bala Lake and a few other places ..	E. 68° S. and E. 68° N.
Barmouth Chain—generally	E. 68° N.
System of the North Berwyns	E. and W.
North of the Dee	E. 34° S.

In Cornwall and Devonshire the prevailing strike of the cleavage-planes is from W.S.W. to E.N.E. In the Lake District the planes of cleavage also usually strike about E.N.E., varying to the E. and N.E. In parts of Yorkshire they run S.E. In the south of Ireland the strike of the cleavage is generally E. and W., except in Valentia, where it is W.S.W.—E.N.E.

As all observations tend to show that the strike of the cleavage is at right angles to the pressure, or parallel to the lines of elevation, it becomes

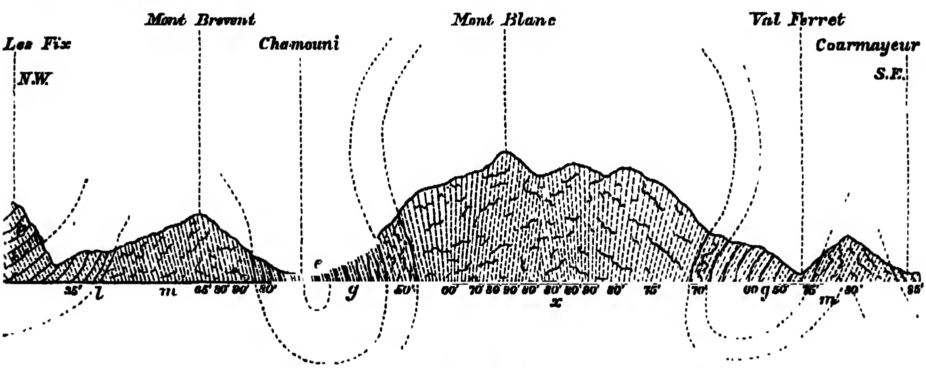


FIG. 141. *Section through the Central Axis of the Alps.* (After Favre; the cleavage dips are Sharpe's.) *x*. Granite (Protogine). *m*. Gneissic and schistose rocks. *j*. Jurassic rocks. *c*. Cretaceous rocks.

a matter of much interest to determine exactly its strike in all mountain districts, as it is probably even more persistent in its direction with reference to lines of axial disturbance than the strike of the beds, which is more subject to the influence of dislocations and other causes of local interference.

The same symmetrical relation of cleavage to lines of elevation through large districts of country, that exists in Westmoreland and Wales, has been found to characterise all mountain chains, whether in Europe, Asia, or America.

It has been long noticed by geologists that in the high chain of the Alps there is an appearance as though the rocks dipped inwards or towards the centre of the range, so that the newer rocks on the flanks of the range seem to dip under the older and crystalline rocks of the central axis. This

[1] Sharpe, 'Quart. Journ. Geol. Soc.,' vol. iii. p. 88.

fan-like structure is now known to be connected with cleavage, and to prevail in all mountain chains where the lateral pressure and flexuring have been excessive. Fig. 141 is a section across the Alps in which this structure is very clearly exhibited. The planes of cleavage are represented by broken lines. Mr. Sharpe considered that, taking the whole breadth of the range, there were as many as nine vertical axes of cleavage.

Professor Rogers was of opinion that in the Appalachian range the dip of the cleavage was influenced by, and varied with, each flexure.

Electrical Action. While there can now be but little doubt that cleavage is essentially connected with lateral pressure, it may be a question whether and how far its development has been influenced by the action of electrical currents. These were shown by Mr. R. W. Fox to have the power of producing such a change in the molecular structure of a homogeneous substance, like clay, as to produce lamination or cleavage. Extended experiments of the same character and with similar results were afterwards made by Mr. R. Hunt[1]. The lamination takes place at right angles to the direction of the current.

Foliation. This is another form of structure partially related to cleavage, though more intimately connected with metamorphic action. Foliation is that structure, generally independent of stratification, in which the rock mass is formed of thin laminæ or folia, each of them consisting of separate mi eral layers or crystals arranged in parallel bands, and with their longer axes placed lengthways coincident with the laminæ, so that the rock splits like an imperfect slate. Such rocks are designated schistose rocks (see Fig. 126, p. 258). A typical example of this structure is that exhibited by gneiss, in which thin plates of mica alternate with quartz and felspar, giving the rock a banded appearance, and often causing it to break up on a large scale into a rough imitation of laminated strata, as shown in the following sketch, Fig. 142, of some gneissic rocks in the Alps.

Mica is the mineral which, in gneiss and mica-schist, gives most prominence to this structure; but talc, chlorite, hornblende, and other minerals may replace the mica, forming the various crystalline rocks known under the terms of *Talc-schist*, *Chlorite-schist*, *Hornblende-schist*, etc. (*ante*, p. 34).

The cause of foliation is a subject of discussion. It is, like cleavage, apparently in some way connected with pressure. Darwin long since pointed out that in the slates of the Andes incipient mineralogical changes have taken place, such as the formation in parallel lines of epidote and chlorite, which are productive of folia, as in ordinary foliation, and he concluded that in most cases foliation and cleavage are parts of the same process. He also noticed that, as in cleaved rocks, the foliation of the rocks

[1] 'Mem. Geol. Surv.,' vol. i. p. 433.

ranged uniformly parallel with the strike for great distances. There is however this essential difference, that slaty cleavage is most developed when the mass of the rock is homogeneous and fine-grained, whereas in schistose rocks the rock is formed of bands of distinct mineral character, and the folia form—not perfectly parallel planes—but consist of somewhat irregular leaves, or of flattened lenticular plates. It would seem that pressure in both cases has been one determining cause, but that the mode of application and conditions have been different.

FIG. 142. *Gneissic Rocks on the road from the Lower Alp to the Middle Hut on the Lysthal.* (Schlagintweit.)

It is evident that where metamorphism has been most intense, foliation is most perfect. Gneiss and mica-schist form one end of a series of which clay-slates form the other. In the latter metamorphic action has not been sufficient to allow of perfectly free motion between the particles, nor to effect the obliteration of the fossils. In the more crystalline schists, on the other hand, the rock has been so softened, that any fossils present have been generally destroyed and lost. In consequence also of the greater plasticity, the separate minerals in these rocks segregated more freely, while also the mass must have yielded more readily to pressure. Slaty structure, as we have seen, is the result of excessive lateral pressure; and from the absence of slaty cleavage in horizontal strata, either the pressure exercised by the weight of the superincumbent rocks would appear to have been insufficient to produce it, or the beds were not in a position to yield. In the case of foliation, have the rocks been rendered sufficiently plastic to yield to the vertical pressure due to superincumbent weight, and so conduce to a tabular arrangement of their particles?

The effects, however, seem to depend not only on heat but also on the lithological composition of the original rock, for there are cases in which the original bedding of the rock is supposed to influence the foliation,—that where the rock has been formed of layers of different mineral composition, the difference is maintained in the foliation, and the foliation is, in those cases, parallel to the bedding. Where the rock was more homogeneous, the influence of bedding has been less felt, and the foliation is at various angles to it. This may be that the foliation took place when the strata were still more or less horizontal and the pressure vertical, whereas in slates the pressure having been lateral the resultant effects were more or less vertical. In the latter, cleavage is entirely independent of bedding, and the coincidence of the two planes is merely accidental. In the former, on the contrary, the original bedding may have influenced the foliation.

I would therefore look upon foliation as partly influenced by the pressure exercised by the overlying strata, while the rocks were undergoing metamorphism and in a position to yield; and as they would retain that foliation during subsequent disturbances, if they then became subjected to lateral pressure and the texture of the rock was favourable, slaty cleavage might supervene on and cross the original foliation at any angle. And in the case of the disturbance having been such as to tilt the foliated rocks at angles vertical or nearly vertical to the horizon, then the planes of cleavage might be parallel to and coincide with the planes of foliation—a result that might frequently occur in greatly disturbed districts.

The fine crumpling, which is so common a feature in foliated rocks, may be due either to ordinary lateral pressure brought to bear after the formation of the folia, or it may possibly have arisen from the lateral expansion of the laminæ, caused by a vertical pressure counteracted by resisting walls, so that the folia are doubled back, as it were, upon themselves.

While therefore cleavage may be considered the result of a maximum lateral pressure with a minimum amount of metamorphic action, and is in the main a mechanical process, foliation may be the result of a maximum amount of metamorphic action, combined with a superincumbent pressure and squeezing, and is mainly a chemical process.

Joints in Stratified Rocks. Another system of divisional planes traversing rocks independently of their bedding is that known under the term of *Joints*. They form partings through the strata perpendicular or at a slight angle to the horizon, and generally at a distance of from two to ten feet apart, although sometimes nearer, and not unfrequently much wider apart. There are usually two systems of joints running at nearly right angles one to the other; and, unlike cleavage-planes, which only affect particular rocks and under certain conditions, they affect rocks of all ages whether of sedimentary or igneous origin, and in all areas, being not less,

or probably more symmetrically developed at points removed from lines of disturbance than near to them.

One set of joints is usually much more marked than the other, and these are called master-joints (*A*, *B*, Fig. 143). One set may be open, and the other so close as hardly to be apparent until the rock comes to be moved. They also become less apparent with the depth from the surface; although it has not been shown that they cease at any depth yet reached.

The effect of such divisional planes, combined with the planes of bedding, is to break up, what would otherwise be a continuous mass or sheet of rock, into rectangular or rhomboidal blocks; and it thereby greatly facilitates the process of extraction, and lightens the labour of the quarry-men. When one of the systems of joints is separated by wide intervals, blocks of rock 20, 50, or even 100 feet long, are sometimes to be obtained.

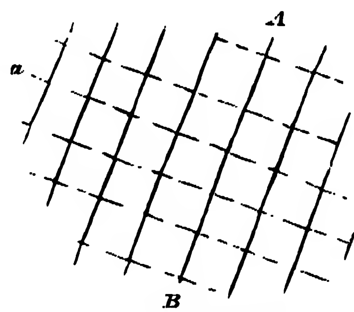


FIG. 143. *Ground-plan of a jointed rock-surfac*

In some cases the joints are rough, and open to the extent of several inches. In others they are, on the contrary, clean and sharp—mere slits. These divisional planes are in fact often as perfect as though cut with a knife, and this is not only the case in fine-grained slates and limestones, but occurs even in some coarse conglomerates (Fig. 144). Such cases are particularly instructive, as indicative of the peculiar and excessive tension to which this symmetrical fissuring, which seems independent of stratigraphical disturbance, is due; for the divisional planes pass clean through all the embedded pebbles, though they may consist of very hard substances, such as quartz, quartzite, veinstone, etc., —much harder than the matrix,—and this independently of any special cleavage the pebbles themselves may have.

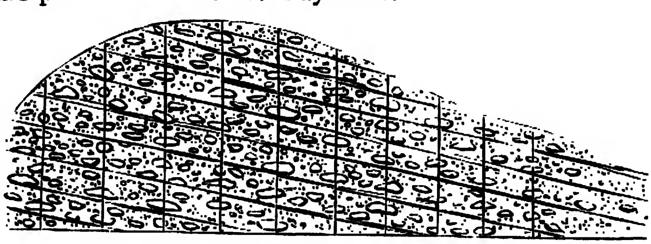


FIG. 144. *Joints passing through Conglomerate strata.*

Direction. Although joints are generally nearly vertical, there are cases where they are inclined at a considerable angle to the horizon, as in those noticed by Professor Harkness in the Carboniferous Limestone of Cork, where a third system of joints cuts the other two at an angle of 45° (Fig. 145). Usually, however, there are in sedimentary strata only two

systems, and these commonly intersect one another at nearly right angles, and are prolonged in straight and definite lines for great distances.

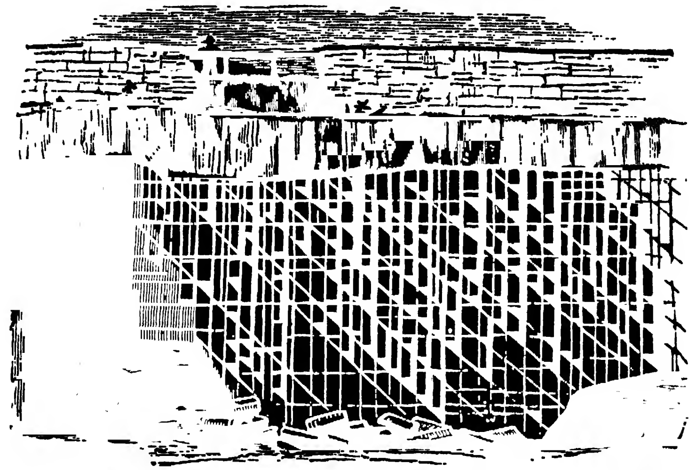


FIG. 145. *Joints in the Carboniferous Limestone at Ballinure near Black Rock, Cork.* (Harkness.)

According to Professor Phillips[1], the main or master-joints in the whole of the Carboniferous series of Yorkshire run nearly all in the same, N. by W. and S. by E., direction, and another important but less continuous set runs nearly E.N.E. and W.S.W., or nearly at right angles one to the other; while the joints in the other groups of strata do not in general vary more

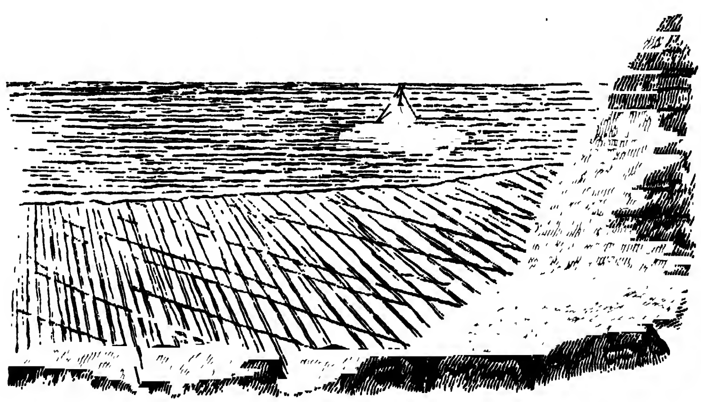


FIG. 146. *View over the jointed limestone, on the Coast of Clare.* (After King.)

than a few degrees from the same course. In the Carboniferous Limestone of Cork, the master-joints run nearly N. and S., and another set nearly E. and W[2]. In Clare, according to Professor King, the jointing of the limestone varies more in its direction, one set running between N. 5° W. and

[1] 'Manual of Geology,' 2nd edit., p. 42, and 'Geology of Yorkshire,' vol. ii. p. 96.

[2] Harkness, 'Quart. Journ. Geol. Soc.,' vol. xv. p. 87.

N.25°E., and the cross joints between E.10°N. and E.15°S. Some of the bare hills in Galway Bay, Fig. 147, are scored by joints from top to bottom. They can be followed for hundreds of yards, and the whole district seems split up by them in a very curious manner [1].

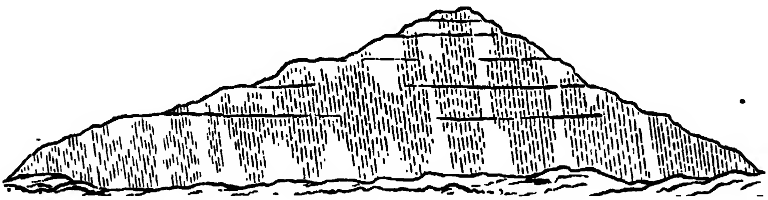


FIG. 147. *View of the Joints in the Carboniferous Limestone of the Hills opposite Galway* (King).

In the neighbourhood of Richmond, Yorkshire, the two sets of joints are so close and regular as to give to the limestone surface, where bare, the appearance of artificial paving.

In the Old Red Sandstone of Waterford the result of a large number of observations gave Dr. Haughton mean directions of N.31 37′W. and of E.32°26′N. for the main joints, or what he terms the first conjugate joints; while the angles respectively formed by this system of joints in the Carboniferous Limestone and in the Old Red measured from east to north, are [2]:—

	Primary.	Secondary.
Old Red Sandstone, *Waterford*	89°.11′ ...	94°.52′.
Carboniferous limestone, *Fermanagh*	94°.18′ ...	91°.20′.

In the Mountain Limestone of the Mendips, near Frome, there are two sets of joints running a few degrees from a right angle one to the other.

In some of the Triassic rocks of Cumberland, and of the Silurian shales of Dumfriesshire, the main jointing is N. and S. In the Devonian slates and limestones of Devonshire, it is 23° to the west of the meridional line.

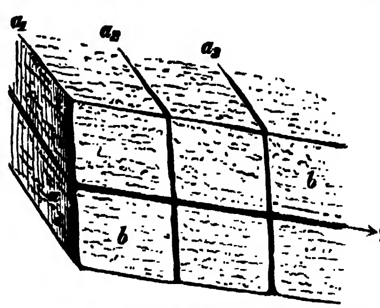


FIG. 148. *Joints in Aymestry Rock* (Phillips).

The joints in the Silurian rocks of Shropshire are sometimes wonderfully regular. In the Abberley district one set, *a*, runs N.9° or 10° W., and another set, *b*, N.87° E.; the dip of the strata being 7° E., as shown in Fig. 148.

The Chalk occasionally shows distinct jointing, especially on the flat

[1] 'Trans. Roy. Irish Acad.,' vol. xxv. p. 605.

[2] 'Phil. Trans.' for 1858, p. 333, and for 1864, p. 393.

surfaces laid bare on some shores, as those on the coast of the Isle of Thanet and of Normandy, in which latter district the main joints run nearly N.E. and S.W., and are crossed by others S.E. by E.

Nor is the jointing less perfect in some Tertiary strata. According to M. Daubrée, the dominant joints in the Paris Basin range within a few degrees of N.N.E. and E.S.E., the angles being seemingly a little more acute in the Fontainebleau sandstones (Fig. 150) than in the Calcaire Grossier (Fig. 149). The regularity of the jointing in some of the sections is remarkable[1].

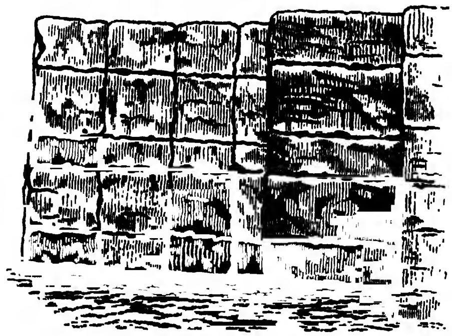


FIG. 149. *Joints in the Calcaire Grossier of Arcueil,* scale $\frac{1}{400}$. (Daubrée.)

It is more difficult to deter- ; of strike of in a disturbed district. M. Daubrée states that in the Tertiary and Jurassic strata of the Alps there is one set of joints varying within the limits of N.E. and N.N.E., and others which approach nearer to E.

The divisional planes (termed *cleat*) which often run through the

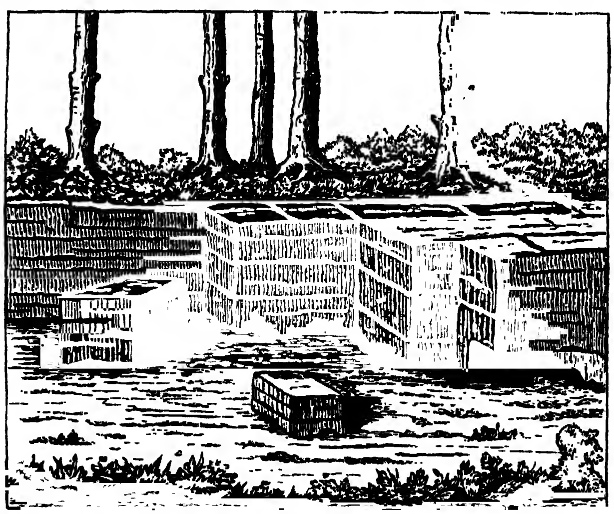


FIG. 150. *Sketch of a Quarry in the Forest of Fontainebleau.* (Daubrée.)

coal in regular vertical, or almost vertical, lines nearly at right angles one to the other, and break up the coal into rectangular masses or fragments of various sizes, are also referred to jointing; but it differs from ordinary jointing inasmuch as it is carried to very small subdivisions.

[1] 'Bull. Soc. Géol. de France,' 3rd ser., vol. vii. p. 108, vol. viii. p. 468, also vol. ix. p. 559.

Although the jointing of rocks has been the subject of frequent observation and remark, the published notices are very much scattered, and there is often a great want of definite information respecting their exact (whether magnetic or true) direction, angles, and grouping. The following are some of the recorded observations arranged in geographical order [1] :—

DIRECTION OF JOINTS IN VARIOUS SEDIMENTARY ROCKS.

District.	Strata.	Place.	Bearing of the joints. First set.	Second set.	Observer.
Cornwall	Slates	St. Ives	N.—N.E.	W. 10° S.	Henwood.
Devonshire	Devonian limestone	South Devon	A few degrees W. of N.	S. of E.	Godwin-Austen.
"	" "	Ippleden, etc.	N. 45° W.	N. 45° E.	"
"	Slates and limestones	Dartmoor	N. 82° E.	N. 23° W.	Pengelly.
"	New Red Sandstone	Sidmouth	N. 1°. 30′ W.	E. 2° N.	Godwin-Austen.
Leicestershire	Slates	Charnwood	N. 24° E.	N. 80° W.	Jukes.
"	"	"	N.	..	"
Yorkshire	Oolite	Helmsley	N.N.W.	..	Phillips.
"	Magnesian limestone	Newton Kyme	N.W.	N.N.E.	"
"	Millstone grit	Dacre, etc.	N.N.W.	E.N.E.	"
"	Carboniferous limestone	Leyburn, etc.	N.N.W.	E.N.E.	"
"	" "	Richmond	N. 25° W.	E. by N.	"
"	Old Red Sandstone	Brough	N. 15° E.	..	"
"	Silurian slates	Ingleton	N.	..	"
Westmoreland	Carboniferous limestone	..	N. 30°. 35′ W.	..	Aveline.
Cumberland	Triassic sandstone	..	N.	..	Harkness.
Waterford	Old Red Sandstone	..	N. 31°. 37′ W.	E. 32°. 26′ N.	Haughton.
"	" "	..	N. 4°. 30′ E.	E. 5°. 50′ S.	"
Fermanagh	Carboniferous limestone	..	N. 25°. 48′ W.	E. 21°. 30′ N.	"
Cork	Yellow sandstones	..	N.	..	Harkness.
"	Carboniferous limestone	..	N.	nearly E.	"
Clare	" "	..	N. 5° W.—N. 25° E.	E. 10° N.—E. 15° S.	King.
Galway	" "	..	N. 27° W.—N. 8° E.	..	"
France	Fontainebleau sandstone	..	N. 23° E.	N. 104° E.	Daubrée.
"	" "	..	N. 23° E.	N. 112° E.	"
"	Gypseous marls	Paris	N. 65° E.	N. 155° E.	"
"	Calcaire grossier	"	N. 18°—27° E.	N. 107°—125° E.	"
"	Chalk	Normandy	N. 50° E.	N. 127° E.	"
Switzerland	Molasse	Clarens	N. 28° E.	N. 113° E.	"
"	Jurassic	Moulieux	N. 35° E.	N. 132° E.	"
"	Lias	La Meillerie	N. 72° E.	N. 129° E.	"
"	Schists	Zermatt	N. 23° E.	N. 129° E.	"

Water-courses. Among the uses to which the joints in limestone districts have served is that of channels for underground waters; and, in consequence of the solvent action of the water, they have often become so enlarged as to give passage to subterranean rivers, and to form caverns frequently of great extent. In limestone districts the hills are sometimes, especially where there have been changes of level, honeycombed with deserted subterranean water-channels.

Symmetry. The joints in sandstones and grits are frequently so perfect as to cause the hill crags to simulate the forms of ruined monuments,

[1] The late Mr. Henwood has given an elaborate record of Joints in vols. v. and viii. of the 'Trans. Roy. Soc. Cornwall,' but the larger number of his observations relate to extra-European rocks.

walls, and towers. In the Millstone-grit of Yorkshire the jointing is often thus regular (Fig. 151), and so it is in the Old Red Sandstone of Waterford.

FIG. 151. *Joints in the Millstone Grit of Yorkshire.* (Geol. Survey Mem.)

In the hill scenery of most countries, Colorado especially, may often be found many singular examples of such phenomena.

Joints in Granite and Igneous Rocks. The joints in crystalline and igneous rocks are not less remarkable than those in sedimentary strata, and they are often so symmetrical as to give to the rocks an appearance of stratification. This is especially the case when they are coupled with a system of horizontal joints, and divide, as in ordinary bedding, the rocks into rectangular and rhomboidal blocks.

In the granites of East Cornwall one set of joints run nearly N.N.W. and S.S.E., and others at angles to it of 70° to 90°. In Dartmoor the joints are more nearly meridional. In the granite and slates of the Mourne and Newry mountains, one dominant set of joints runs between 5° and 15° W. of N., and another between 15° and 25° E. of N.; while in Donegal they run between 10° E. of N. and 10° W. of N., and between 10° N. of E. and 10° S. of E.

District.*	Rocks.	Place.	First set.	Second set.	Observer.
Cornwall ...	Granite	Penrhyn	N.N.W. ...	... ...	Enys.
„ ...	„	... ...	N. 25° W. ...	... ...	De la Beche.
„ ...	Serpentine ...	... ...	N. 25° W. ...	... ...	„
Cornwall, E.	Granite	Caradon	N. 35° W. ...	E. 23° N.... ...	Henwood.
„	„	„	W. 20° N. ...	... ...	„
„ W.	„	Helston	N.W.	N. 20° E.... ...	„
„	„	„	N. 20° W. ...	... ...	„
Cornwall ...	Granite and slate	... ...	N. 32°. 55′ W.	E. 32°. 34′ N. ...	Haughton.
„ ...	„ „	... ...	N. 6° W. ...	E. 4° N.	„
Devon ...	Granite	Dartmoor	N. by W. ... N.W. by N.	E. by N.... ...	Ormerod.
Newry ...	Granite and slate	... ...	E. 37°. 48′ N.	N. 37°.—48° W.	Haughton.
Donegal ...	„ „ etc.	... ...	N. 5°. 15′ W.	E. 10°.—20° N.	„

The sharpness of the jointing in granite, though frequently obscured by weathering, which rounds off the angles, gives the rocks a roughly columnar appearance very apparent in many cliff sections (Fig. 16). Where

the granite better resists decomposition, the isolated masses sometimes assume the regularity of an artificial structure (Fig. 152).

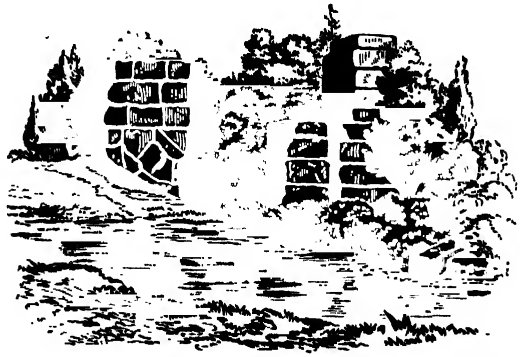


FIG. 152. *Jointed structure in the Granite of Carlsbad.* (Daubrée.)

In other crystalline and igneous rocks the system of joints is more complicated, and gives rise to the prismatic structure so common in basaltic rocks, and not infrequent in felsites and other acidic rocks. The following example of a vein of diorite traversing Bala slates is interesting, as it shows both the columnar structure of the intruded rock (*c*) and the cleavage of the associated slates (*a*), while the altered rock (*b*) in contact with the diorites is not affected by cleavage.

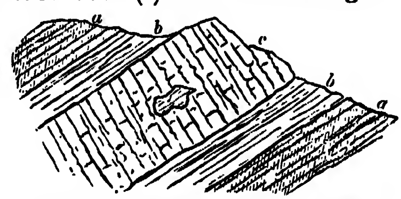


FIG. 153. *Section near Ffestiniog.* (Ramsay.) *a.* Cleaved slate; *b.* Altered slate not cleaved; *c.* Diorite: roughly columnar.

There are instances also where a combination of joints causes some porphyries to split into very regular parallelopipeds.

Origin of Jointed Structure. The origin of joints is not well understood. It has been referred to contraction and shrinkage of the rocks in the process of drying and consolidation; to tension; to a sort of incipient crystallisation; and to the influence of polar magnetism.

There is no doubt that in the desiccation of sedimentary strata there has been contraction, but we can scarcely attribute to contraction alone the symmetrical forms given to the strata by joints, and much less would it be possible to explain by mere shrinkage the smooth, close and regular plane surfaces in limestones, and the incisive divisional planes in conglomerates.

The long rectilinear course of joints and their symmetrical arrangement have been attributed to the uplifting of the strata, which, by causing strains at right angles to the slopes, has tended to open fissures or joints in lines parallel to the strike of the strata. It is true that joints are often parallel to axes of elevation, but they are not uniformly so; and it may be a question whether that parallelism is not owing to the circumstance

that the lines of joints are lines of least resistance, which may in some cases have influenced the direction of the elevatory force. Further, although a strong strain might be produced when the strata were uplifted at a considerable angle, the strain would diminish with the angle, and would be inappreciable in those large continental areas of elevation where the strata have been moved little, or not at all, out of their original horizontal position. The strike of the joints also is not always uniform with that of the strata.

Smoothness of Jointing. The smooth and even surfaces of joints in conglomerates are perfectly inexplicable by shrinkage. If the strata were merely torn asunder, as they would be by shrinkage alone, the pebbles in such strata, usually harder than the matrix itself, would remain unbroken, and stand out in relief on the fractured surfaces. Although this happens in some cases, it happens as frequently, if not more so, that the joints cut clean through matrix and pebbles, as though it were done by a sharp cutting instrument, while there is no difference of level between the fractured surfaces to indicate the action of shifting or of pressure.

There would seem to be in these conditions an indication of the influence of something analogous to the force of a cleavage,—not that resulting from pressure, as in slate rocks,—but that which in crystallisation causes the molecules of the crystals to group themselves in planes with surfaces of least resistance.

This arrangement of the particles of the rock,—if it may be so expressed,—as solidification took place, is best exhibited in some calcareous strata. The joints of the Carboniferous Limestone in the Mendip district approximate sometimes very closely to the angles of rhomboids of carbonate of lime. In Devonshire Mr. Godwin-Austen[1] has described the main set in the Devonian Limestone as running a few degrees W. of N., and a cross set S. of E. (approximately an angle of about 100°) with local variations; while Mr. Pengelly more precisely fixes the bearing of the joints at N. 82° E. and N. 23° W., which gives an exact angle of 105°, or that of calc-spar. Professor Harkness also states that the joints in the pure Devonian limestones of Cork cause them to divide into masses having a rhomboidal form, in accordance with the cleavage of calc-spar.

But these angles are, as we have shown, subject to great variations—variations which may be dependent upon the greater or less mineral purity of the rock, or to the differences in mineral composition. In county Clare the angles in the Carboniferous Limestone vary from 85° to 110°; while in Yorkshire they vary from 80° to 102° and 113°; in Fermanagh they are 94° 18′ and 91° 20′, or more nearly at right angles, as they are at Cork. In the calcaire grossier of Paris the joints would seem, judging from the lists

[1] 'Trans. Geol. Soc.,' 2nd ser., vol. vi. p. 463.

given by M. Daubrée, to be at right angles, with occasional exceptions of angles of about 80° and 107°.

As a rule there is no doubt that joints, whether in calcareous or in arenaceous strata, run more generally nearly at right angles than at any other. In the latter class of rocks this is however more uniformly the case than in the former, as for example in the New Red Sandstone of South Devonshire, and the Millstone-grit of Yorkshire.

Regularity of Form. Nevertheless, as there are indications that, with the more compact and crystalline structure of the limestones, the joints tend more and more to cross at angles approaching those of calcite, so in other rocks instances are found of the base influencing the directions of the joints, just as the base of lime-carbonate has determined the crystallisation in rhomboids of portions of the Fontainebleau Sands. Another case in point occurs in the Palæozoic rocks (those with *Oldhamia*) of Bray Head, near Dublin. Mr. Gages[1] states that the schist there, which has a felspathic base, and has been highly metamorphosed,

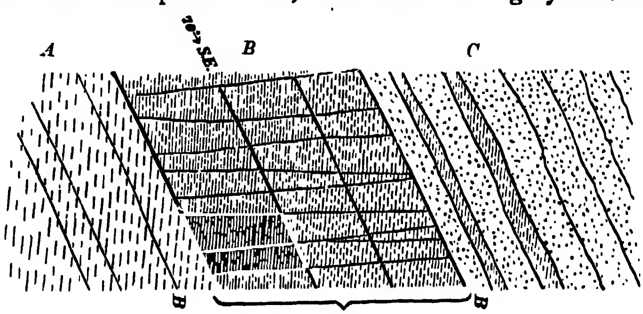


FIG. 154. *Section of Aberllefenny Slate, Merionethshire.* (C. Le Neve Foster).

is remarkable for its system of joints, which cause it to separate into rhomboidal prisms presenting the angles of cleavage of orthoclase felspar, the planes of bedding corresponding to one of the planes of cleavage. Even in the more arenaceous metamorphosed beds of the same formation, the crystalline forms of orthoclase have impressed themselves in a rude way on the rock.

The symmetrical manner in which slates break has often been noticed, but in these rocks complications are introduced by interferences between the planes of cleavage and of joints. In the slates in the neighbourhood of Kirby Lonsdale, Professor Phillips found the two sets of joints crossing at angles of 68° and 112° and at right angles, but he observes that these angles vary slightly in every quarry. Near Cherbourg the angles formed by the jointed fragments of both the grey and the green slates are constant at 64°, 108°, and 83°.[2]

[1] 'Reports Brit. Assoc.' for 1863, p. 207.

[2] Phillips' 'Yorkshire,' vol. ii. p. 6; and W. B. Clarke, 'Trans. Geol. Soc.,' 2nd ser., vol. vi. p. 565.

An interesting section (Fig. 154) is given by Dr. Le Neve Foster of the slate mine at Aberllefenny. A bed of slate, *B*, about 60 feet thick lies between *A*, an imperfect slate, and argillaceous uncleaved grits with seams of slate, *C*. The dip of the beds is 70° S.E., while the cleavage is nearly vertical, and coincides with the strike of the bed. The slate is traversed by sets of joints. One set of flat joints, from 2 to 10 feet apart, runs from wall to wall. Another set, erect with a steep dip N.E. or S.W., runs from N.W. to S.E. at right angles to the strike. Nearly parallel with the last is a third set of planes dipping N.E. at an angle of about 80°. The intersection of these several planes and the joints divides the slate into rough parallelopipeds.

The jointed structure of granite is, as already mentioned, one of a very marked character, dividing the rock into roughly rectangular or rhomboidal blocks of various sizes (Figs. 16 and 152). The angles at which the joints meet seem to vary from nearly a right angle to angles of 130° or more. The mean of a number of observations gave Dr. Haughton for the granites of Ireland and Cornwall—

	Donegal.	Mourne Mountains.	Cornwall.
Primary joints ...	93° 19′	88° 51′	90° 21′.
Secondary " ...	... ...	90°.	92° 30′.

In Dartmoor the joints form angles of from 88° to 122°.

Although the quartz in granite was the last to solidify, the joints seem more nearly coincident with the forms of felspar than of quartz. Orthoclase cleaves most readily in two planes, having an angle of 90°; albite of 86° 30′; and labradorite of 93° 30′ and 86° 30. These angles are frequently very closely represented in the jointing of granite, larger angles being exceptional and governed possibly by some of the other planes of the felspars, or due to variability of composition. Are we to suppose therefore that the quartz, which forms 30 to 40 per cent. of the granite, yielded to the more predominant felspar? There is the objection that the crystals of felspar are sometimes cut through by the planes of jointing; but how far does their cleavage conform to that of the joints? On the other hand, quartz though crystallising usually in six-sided prisms, has for its primary form a rhomboid with angles of 94° 15′ and 85° 45′. The prism is the usual form when silica has crystallised out of a liquid solution; but, if a prism of rock-crystal be exposed to a high temperature and then suddenly cooled, planes of cleavage become apparent in the direction of the primary rhomboid [1]. There is therefore a presumption, supposing the existence of such a molecular force as this implies during the cooling of granites from a molten state, that this latent crystalline form of quartz may have influenced the direction of the main joints.

Columnar Structure. By far, however, the most remarkable

[1] Dufresnoy's 'Minéralogie,' vol. ii. p. 132.

exhibitions of jointed or prismatic structure are those which occur in basaltic rocks, as in the well-known instances of the fine colonnades of the Giant's Causeway, Staffa (Fig. 155), the Cantal and Ardèche (see Scrope's 'Auvergne'), the Rhenish Provinces, Bavaria, the Vicentino, the Palisades of the Hudson (U.S.), and of many other basaltic districts.

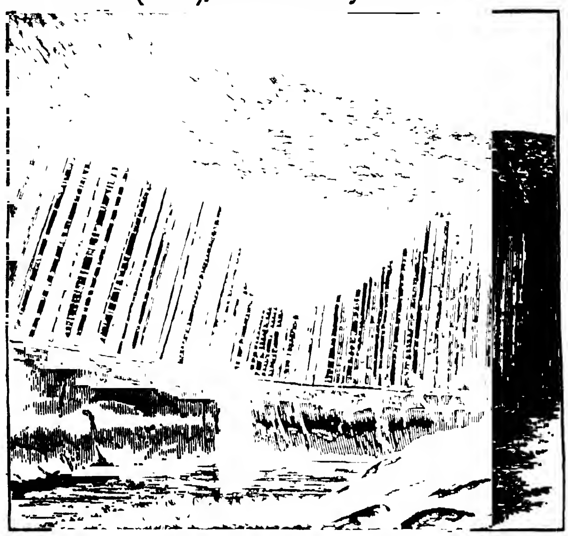
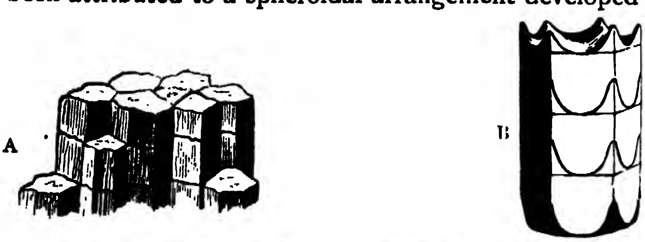


FIG. 155. *The Boat Cave, Staffa.* (From a photograph.)

The prismatic structure is generally confined to certain layers of the basalt, as in the above figure, the columns ending abruptly against structureless masses of basalt. The columns are, however, always at right angles to the cooling surfaces, and therefore may be at all angles to the horizon; and when the basalt forms a vertical dyke, the columns lie horizontally, with all the regularity of a pile of wood logs.

The prismatic columns and cup-and-ball jointing of basaltic rocks have been attributed to a spheroidal arrangement developed by the rock in

A



B

FIG. 156. A. *Ordinary Basaltic Column.* B. *Column showing Ball and Socket structure.* (Scrope).

cooling. It was supposed that the mass segregated into a number of spherical concretions, and that these spheroids, pressing against one another, gradually assumed prismatic forms, and gave rise to the polygonal columnar structure so common in these and other igneous rocks (A, Fig. 156).

But this view has been contested by many later observers [1], who have pointed out, amongst several objections, the difficulty of supposing how, by pressure alone, the centres of these spheroids could have become arranged in straight lines like beads on a string; or of accounting for columns, often of small diameter, formed of unbroken prisms 20 to 50 feet in length. They are of opinion that prismatic structure is due to the contraction through slow cooling of a homogeneous mass, and refer the spheroidal structure to exfoliation consequent on the weathering and gradual decomposition of the cuboidal blocks of the rock. But this offers no sufficient explanation of the origin of the transverse joints, and of the cup-and-ball structure. Scrope considered it to be a combined result of contraction and concretionary attraction.

In a later and exhaustive paper [2], Professor Bonney considers that all the divisional structures which can be observed in igneous rocks, are to be referred to one and the same cause, viz. contraction of the mass while cooling. Although cuboidal blocks of rock have a tendency to weather into rough spheroids, and the further action of the weather might occasionally produce concentric exfoliation in such spheroids, he shows that 'spheroidal structure is to be seen in rocks which are not homogeneous, and are not at all cuboidal in form,' and that 'spheroids may be found in columnar rock which have evidently been formed inside a prism, the exterior of which was not broken by joints.' The hexagonal form of the columns is the figure which results from uniform contraction in two dimensions, while he refers the spherical structure to contraction in three dimensions.

The peculiar cup-and-ball structure of basaltic columns is explained by Prof. Bonney on the principle that it is a special case of the spheroidal structure, connected with the division of the columns into approximately equal lengths, respecting the exact cause of which there is still, however, some doubt. But the student should consult the paper itself.

Nevertheless I feel a difficulty in assigning to unaided contraction alone the wonderfully symmetrical structure of basaltic colonnades. In all the cases of columnar structure the rocks have a base of felspar, or of felspar (generally labradorite) with hornblende or augite. Now, one of the crystalline forms of labradorite (that, for example, in the lava of Etna) is a hexagonal prism. This also is a common form of hornblende, and not an uncommon secondary form of augite, and they all cleave in three planes. The tendency also of amphibolic minerals to crystallise in long prisms deserves remark.

Crystalline Action. Here, therefore, as in granite, there are, I consider, grounds for inferring that the direction of the joints in the

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[1] Poulett-Scrope, 'Volcanos,' 2nd edit., p. 102; Professor Jas. Thomson, 'Reports of Belfast Naturalists' Field Club, 1870;' R. Mallet, 'Phil. Mag.' for Aug. and Sept., 1875.

[2] 'On Columnar, Fissile, and Spheroidal Structure,' 'Quart. Journ. Geol. Soc.,' vol. xxxii. p. 140.

rocks may have been determined by a process of incipient crystallisation. Have we not some confirmation of this in the facility with which the quarrymen can 'dress' some such rocks,—as, for example, granite,—in certain directions and not in others? The primary cause of *jointing* is, there is little doubt, the contraction induced by cooling: but just as the cooling of mineral solutions on the sides of fissures in rocks has determined the deposition of crystals of quartz and other minerals against the walls of the veins, with their longer axes at right angles to the walls, so the cooling on the sides of a basaltic dyke may have determined the direction of the basaltic prisms perpendicular to the walls of the fissure not only in the sense of the contraction due to the cooling, but in the sense of an analogous condition to that which has determined the crystalline action.

The system of joints, therefore, seems to me to be not a simple mechanical action, but one combined with a condition of crystallisation; and though, from the influences of other mechanical forces to which the rocks have been exposed, and from the varying proportions of their constituent ingredients, we cannot expect the angles to present the exact definition which a crystal of the pure mineral would have, still there is every appearance of the plane-lines of shrinkage and the jointing having been guided in many cases, if not in all, by planes of crystalline cleavage in consequence of these being those of least resistance.

Professor W. King divides joints into *meridional* and *equatorial* systems. He also considers that jointing is not a mechanical but a physical phenomenon; and suggests that both it and cleavage are due to the same laws operating under modified conditions, and that they are both in some way obedient to crystalline polarity. He further suggests that the meridional jointing has varied with the secular variation of the magnetic meridian, which no doubt varied in geological times as it does at the present time—the variation having between the years 1580 and 1814 ranged from 11° 20′ east of north to 22° 34′ west of north[1].

Age of Joints. With regard to the time at which jointing followed on the consolidation of the rocks, it is not easy to find a measure of this time-interval. Triassic fossils are found in joints of the Carboniferous Limestone of the Mendips; and large joints in the Devonian limestones of Plymouth and Torquay existed before the Trias, for they are found filled with the New Red Sandstone which overlies[2]. Some even of the most recent rocks are jointed, for jointing has been observed in the cliffs of compact coral-limestone in those islands in the Pacific which are formed of raised reefs.

On the other hand, we have to note that slate-rocks are traversed by joints apparently formed subsequently to the cleavage; so that they

[1] 'Trans. Roy. Irish Acad.,' xxv. p. 605.
[2] Pengelly, 'Devon. Assoc. Sc. and Ant.' for 1863.

would seem to have been disturbed and upheaved before they became jointed. Again, joints are found in highly inclined strata at right angles to the planes of bedding, showing that the jointing took place before the upheaval. Further, if jointing were connected with elevation of the rock, the shrinkage of the strata would have some relation to synchronous periods of time, which is scarcely possible, for it would involve indefinite periods for the process taking place. Nevertheless it frequently happens that rocks of very different ages, such as the granites and slates of Cornwall, or the porphyries and Permian sandstones of Ireland, are jointed in a like manner, while in others, as in the case of the Carboniferous Limestones and the Dolomitic strata of Cork, the jointing is different; but this may depend on local circumstances, or may be a further proof of an independent crystalline action.

Importance of Joints. The important part played by joints in many geological phenomena, and the obscurity in which the subject is yet to a great extent enveloped, have induced me to devote to it a larger space than I had contemplated. The effects of joints in influencing the direction of mineral veins have been long noticed by miners; a somewhat more uncertain relation between joints and faults has not been overlooked: the connection of lines of joint with lines of strike of the strata has led to inferences respecting the dependence of the one on the other; and the marked bearing of the symmetrically jointed rocks on the physical features of a country has not failed to attract attention.

But besides these relations, there are others of great interest which leave much to be desired, and to which further attention might with advantage be directed. Lines of joint being lines of least resistance, their influence in shaping, modifying, or diverting movements of upheaval, should be examined into. M. Daubrée[1] has shown that many valleys of the north of France are on the line of strike of the joints, and points out the influence which this may possibly have had upon the direction of the denudation and river-systems of the country. The influence of joints on coast-lines, and even on the form of continents, opens a large field of inquiry[2]; and at the same time the physical and chemical questions connected with their origin are of the greatest interest and involve relations of symmetry upon a scale of vast grandeur. For, while there clearly exists a symmetry of structure which, however obscure in its origin, is known to affect the very smallest groups of molecules, an analogous force of symmetry would seem to have influenced the structure and arrangement of the great rock-masses, and to have made its effects felt throughout the outer solid framework of the globe.

[1] 'Géologie Expérimentale,' p. 362.

[2] As having some bearing on this point, see the Rev. Robert Everest's paper 'On the lines of deepest water around the British Isles,' 'Quart. Journ. Geol. Soc.,' vol. xxii. p. 37.

CHAPTER XVII.

MOUNTAIN-RANGES.

DIFFERENCE BETWEEN CONTINENTAL AND MOUNTAIN UPHEAVALS. RELATIVE AGES OF MOUNTAIN RANGES. COMPLEX NATURE OF THE RANGES. DIRECTIONS OF THE RANGES. ELIE DE BEAUMONT'S HYPOTHESIS; OBJECTIONS TO IT. NUMBER OF MOUNTAIN SYSTEMS. LIST OF EUROPEAN SYSTEMS. SYSTEMS IN OTHER PARTS OF THE WORLD. THE SEVERAL EPOCHS OF DISTURBANCE. RANGES OF ARCHÆAN AND PALÆOZOIC DATE; PRE-CAMBRIAN RIDGES; THE LONGMYND; THE GREEN MOUNTAINS, U. S. A.; WESTMORELAND AND THE SCOTCH MOUNTAINS; THE PENNINE CHAIN; THE MALVERNS; THE MENDIPS AND THE ARDENNES; THE APPALACHIANS AND ALLEGHANIES. RANGES OF MESOZOIC DATE; THE VOSGES; NORTH SCANDINAVIA; THE THÜRINGERWALD; THE ERZGEBIRGE; THE SIERRA NEVADA. RANGES OF TERTIARY DATE; THE PYRENEES; THE CENTRAL APENNINES; THE WEALD; THE AXIS OF THE ISLE OF WIGHT; THE JURA MOUNTAINS; THE MAIN ALPS; THE HIMALAYAS; THE ANDES.

Continental and Mountain Upheavals. Great continental upheavals, such as those described in Chapters XIII and XIV, may affect very large areas, and may raise wide districts to considerable heights above the sea-level, without much disturbance of the strata and without throwing them materially out of the horizontal; for example, in the case of the extensive Chalk and Tertiary plains of Southern England, Belgium, and Northern France, and other large continental tracts, where, with the exception of an occasional short and narrow anticlinal axis, the strata stretch over thousands of square miles, scarcely varying in their dip more than from 2° to 5° from the horizontal; and with great breadths with comparatively few faults, and those generally of small dimensions.

In all parts of the world, however, these uniformly uplifted areas are bounded by comparatively narrow bands or zones, more or less rectilinear, within which the strata have been tilted at high angles, and folded and compressed into colossal ridges; here also the tilting and compression have been accompanied by enormous faulting and wonderful inversions of the strata. Whereas *continental elevation* may take place with or without fracture, *mountain-elevation* is always accompanied by powerful fracture and excessive lateral pressure. Both forms of upheaval are due to the operation of the same subterranean forces; but, while we have knowledge within our own experience of the operation of the former, we have, within

the same experience, no knowledge of the latter, and can only judge, by inference from the facts, of its mode of action.

Relative Age of Mountain-Ranges. Mountain-ranges are of all geological dates, and their relative ages are determinable by unconformity of superposition (*ante*, p. 251). Thus in Diagram 1, Fig. 157, the strata, *s*, were raised, and the ridge or anticline, *A*, was formed, before the deposition of the strata or formation, *p*, which range up to and abut horizontally against or overlie unconformably the older strata *s*. In this case the mountain-chain is said to be of an age newer than the strata *s* and older than *p*, which is unaffected by the uplift.

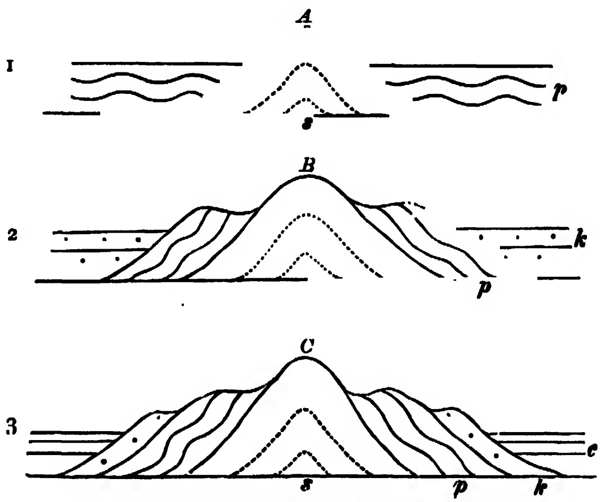

FIG. 157. *Diagrams showing relative age of Mountain Chains.*

Or it may be that *p* also has been tilted, raised, and overlain unconformably by *k*, which indicates a later period of elevation for the chain, *B*; or, in the case of another chain *C*, *k* may have been raised and the strata *c* deposited, and, as they are undisturbed, it follows that the chain is more recent than *k* and older than *c*. Or again, it may be that the three disturbances have affected the same chain, in which case, although *s*, *p* and *k* are all tilted, there would be an unconformity between each of them; this is not shown in the diagram, but its consequences are apparent in Fig. 167, p. 301. The upheaval of a mountain-range may in this way be ascertained to have taken place either at one period, or at different times and so prolonged through long successive geological periods. Nevertheless it is found that there is usually one dominant and chief line of axial disturbance, which gives the conspicuous *relief* to the range; and it is the age of this more important upheaval, which is generally the last or nearly the last, that it is usual to speak of as being that of the mountain-range as a whole; but it must be borne in mind that this age only refers to a final period of highest

upheaval, and that the first deformation of that part of the earth's crust may have commenced at a period long anterior.

Complex nature of the Ranges. Mountain-ranges are rarely limited to a single ridge, but consist usually of a series of more or less parallel anticlinal ridges, broken by transverse passes, and separated by synclinal valleys. These ridges may be prolonged for a few miles only, or may extend for hundreds of miles. Sometimes one axial line of disturbance will die out and be succeeded by another at a short distance from, but parallel to it; and this may be replaced by a third, or by more lines, giving to the mountain-range an apparent curve, though really formed of a succession of parallel ridges 'en echelon.' Generally, however, either by long, linear prolongation, or by successive replacements, mountain-chains stretch in belts, more or less approaching to the rectilinear, along and across wide continental areas.

When important lines of axial disturbance cross one another, the structure of the chain becomes still more complex and the isolation of the separate lines less apparent. It is to interference of this character and to the frequency of synclinal troughs, and fractured foldings consequent thereon, that much of the variety and beauty of the Alpine scenery is due. Where, on the other hand, the mountains rise more gradually and there is less complication, the synclinal troughs may be broad, and may even form high plains and plateaux, such as those of the Great Salt Basin in the Rocky Mountains, and of Thibet in the Himalayas. When in addition the gradients are small, the mountains lose much of their grandeur and apparent importance. In the Andes the eastern slope is only about 60 feet in a mile, but the western slope equals 100 to 150 feet in a mile. In some mountain-ranges the slopes are still less. The average eastern slope of the Rocky Mountains seldom exceeds 10 feet in a mile, or about 1 foot in 500. On the western side the average slope is but little less gradual. The rise on the eastern side continues for 600 miles, and the fall on the other side for 400 to 500 miles. It is on these flat arches, which resemble a continental elevation with a line of fracture and compression along their crest, that the final steep mountain ridge rises.

Direction of the Ranges. In 1829 M. Elie de Beaumont advanced the proposition that not only were the great mountain-ranges of different ages, but also that those of different ages had different directions, and that there was a parallelism between those of cotemporaneous age. In a later work[1] he enlarged the number of distinct ranges, and grouped them in a manner to show the presumed existence of certain symmetrical relations between the different parallel systems; while in his last great work[2] on the subject M. de Beaumont extended his researches to

[1] 'Systèmes de Montagnes,' 1852.

[2] 'Rapport sur la Stratigraphie,' 1869. See also 'Comptes Rendus,' vol. lvii. and lviii.

other parts of the world, and developed more fully his theoretical views on the subject of his *réseau pentagonal*.

Owing to the circumstance that, in the first instance, the distinguished French geologist restricted to one period the limits in time of each mountain-range, and attributed to single upheavals mountain-ranges which he subsequently admitted to be the result of many disturbances, together with the novel theoretical views with which his researches were connected, his important and interesting works—works which have had wide acceptance amongst foreign geologists and have greatly influenced continental scientific opinion—have scarcely received sufficient attention in this country.

The attitude of English geologists was greatly influenced by the valuable review of the subject by Mr. W. Hopkins, in 1835 [1], which, while contending chiefly against the theoretical views of Elie de Beaumont, endeavoured to show, upon the evidence especially of the geological structure of Wales and the adjoining English counties, that the lines of disturbance were as a rule much too complicated to be reduced to the simple forms of expression proposed by M. de Beaumont. At the same time Mr. Hopkins observed the one part might be true to the fullest extent to which it was asserted, while the second (or theoretical) part might have no real foundation to rest upon.

M. Elie de Beaumont's Hypothesis. M. de Beaumont's researches may be divided into two parts, but they are so intimately connected, and the facts have been adjusted with such geometrical precision in order to be adapted to the exigencies of the formulæ, that it is difficult to separate them. Into the complicated theoretical question of the *réseau pentagonal*, which involves an elaborate mathematical investigation, this is not the place to enter. To understand it, the student should refer to M. de Beaumont's several works on the subject, and to Mr. Hopkins's paper, where it is discussed in its geometrical bearing [2].

Before, however, dismissing this part of M. de Beaumont's hypothesis, I may briefly allude to certain points in it with reference to some purely geological objections that present themselves. For example, the purposes of the hypothesis require that the angles formed with the meridian by each line of disturbance should be determined with the utmost exactness—not only to *degrees*, but to *minutes*. Now, every field geologist knows the difficulty of determining exactly a line of strike, and he knows also how liable it is to variations, within the limits of several degrees, in the course of even a short range. Although M. de Beaumont did not overlook this point, and, in all cases, took the mean of a large number of observations, every fresh observation is likely to affect that mean, though it may be to some only small degree; but even this, with the multiplicity of systems and the

[1] 'Anniv. Address, Quart. Journ. Geol. Soc.,' 1853.

[2] A clear summary of the principles of this system will be found in M. de Lapparent's 'Traité de Géologie,' Paris, 1883, p. 1239.

near parallelism of many of them, renders the differences *inter se* as great as those *inter alia.* Nor is it sure but that some lines of disturbance are curved and not straight, as that of the Wealden elevation, and even of the Alps, if, as some geologists contend, the two great Alpine axes are of synchronous and not of separate age.

If we were dealing with a perfectly homogeneous body, and one subject to internal influences only, we might possibly have, as in a crystal, definite symmetrical planes developed; but in a body like the earth, where external influences are constantly modifying the surface, conditions exist which could hardly fail to interfere to a greater or less extent with the direction in which the subterranean forces are developed on the surface, just as a scratch on a pane of glass will determine the direction of the line of fracture. The external agencies may be in the form of denudation weakening one part of the crust and strengthening another, or it may be in the varying resistances offered by rocks of very different degrees of hardness and thickness, or in an influence exercised by the lines of joints. It is true that, looking at the enormous forces in operation, the external agencies may have but a qualified influence in determining the general bearing of great lines of disturbance; but they will surely have enough to disturb the, as it were, goniometric precision on which the investigation is based.

Another objection is that, where the disturbance is accompanied by the protrusion of great bosses of erupted rocks, such as the granitic centres of Cornwall and Devon, these masses cause strains in the strata through which they have been upheaved, tangential to their circumference, so that, while the main disturbance may maintain one general axial line, the strata must be subjected in places to fractures approximating more or less to the tangent of the semi-circumference of the several granitic masses. It is this, I imagine, that has led M. Moissonet to conclude, that in so limited an area as that of Cornwall, the directions of the faults and mineral veins correspond and are contemporaneous with no fewer than *eleven* out of the twenty-one great mountain-systems of Europe. That there have been disturbances there at different geological periods, and that these differ on their directions, there can be no doubt; but with the many causes of interference, and the many local deviations, it would be possible, by adapting so precise a value to every small difference in the angles, to form an almost indefinite number of systems.

Instead of the great lines of elevation and disturbance on the surface of the earth resulting from a definite symmetrical system, it would seem, now that the antiquity of the continents and great ocean-basins is better understood, that their direction, on the whole, has been governed in most cases by the position and form of existing continental areas and by antecedent lines of weakness, and that the great areas occupied by the oceans, although subject to upheaval and depression *en masse,* have not been

subject, within the later geological periods, to disturbances in the nature of mountain compression and elevation.

Nevertheless there are involved in the original idea of M. de Beaumont consequences of the greatest geological importance and interest relating to the mode of formation, relative ages, and grouping of mountain-ranges; and although we may hesitate to accept his rigorous orientations, we have no such hesitation in accepting, with limitations, his more general views. It is easy to find exceptions to the rules, but these exceptions may often be immaterial, or may arise from attempting to overstrain the hypothesis, or from attention to the smaller details causing the larger generalities to be overlooked. Much, however, remains to be done before the problem can be satisfactorily solved.

Summary of Elie de Beaumont's Hypothesis. Apart from the theoretical views, the three great propositions sought to be established by M. Elie de Beaumont were—1st, the relative age of mountain-ranges; 2ndly, the synchronism of ranges situated on lines parallel one to another; and 3rdly, that the magnitude and height of mountain-ranges increase as we approach the latest geological periods.

FIG. 158. *Sketch-map of Europe, showing the orientation, in their chief centres, of the principal mountain chains* (see p. 292).

By parallelism, in the sense used by M. de Beaumont, is meant straight lines parallel to great circles of the sphere drawn through and in the

direction of any of the central systems on the surface, and passing through the centre of the sphere. Straight lines parallel to these form smaller circles on either side of the great circles. Consequently each of these circles intersects the meridians in different latitudes at different angles; thus the 'System of the Netherlands,' which at Mons intersects the meridian at an angle of E. 5° N., transposed to Milford Haven, there intersects the meridian at an angle of E. 11° 54′ N.: in Yorkshire the 'System of the North of England' bears N. 5° W., and in Cornwall N. 8° 7′ W., while in Greece it bears N. 10° 44′ E. This will be best understood by reference to the diagram (Fig. 158).

Number of Mountain Systems. In 1852 Elie de Beaumont had determined the relative age and direction of twenty-one mountain systems in Europe, first basing those directions on the bearing of each system in their several centres in relation to its own meridian. In order, however, to determine the angles they respectively form with one another, he transposes them to common centres, of which he takes three, namely Corinth, Binger-loch, and Milford Haven. I have selected the last, as being the most convenient to British geologists, to which to refer the orientation of the mountain-ranges in the following Table. The orientation at the place which serves as the type locality is given in parentheses, and the period of upheaval is shown by the position of the *system* between the geological Formations placed *above* and *below* it. Thus the system of elevation of Westmoreland took place at the close of the Upper Silurian period, and before the beginning of the Devonian period; and the system of the Netherlands between Permian and Triassic times.

Any of the strata that precede each system may have been subject to the disturbance; while all those which succeed and are newer were deposited horizontally upon the older disturbed strata after each upheaval. Each system bears the name of the one main centre of that particular disturbance. To these are added the names of some other principal places, where evidence of the same system of disturbance has been recognised by M. de Beaumont[1], together with a few on the authority of American and other geologists. Where there seems a doubt respecting the exact geological horizon of a system, I have placed the supposed geological period within brackets: it must also be of course understood that with the progress of stratigraphical geology some modification of these horizons may be rendered necessary.

TABLE OF THE MOUNTAIN-SYSTEMS OF EUROPE, WITH THEIR LOCAL AND RELATIVE BEARINGS, THEIR GEOLOGICAL POSITION AND AGE, AND CONTEMPORARY RANGES.

	Orientation on the meridian of Milford Haven.
Schists of Belle-Ile [*Pre-Cambrian?*].	
I. **System of La Vendée** (Brittany, N.N.W. to S.S.E.)	N. 24° 14′ W.
Parts of Brittany, Ross-shire.	

[1] In the 'Systèmes de Montagnes,' 1852, will be found full details of the places affected.

		Orientation on the meridian of Milford Haven.
	Cambrian (Lower?).	
II.	**System of Finisterre** (Brest, E. 21° 45′ N.)	E. 22° 10′ N.
	Brittany, Normandy, the Maures Mountains, the Pyrenees (?), Pembrokeshire, Scotland, Sweden, Finland, Catalonia, Corsica.	
	Cambrian [Upper?].	
III.	**System of the Longmynd** (Church Stretton, N. 25° E.)	N. 21° 24′ E.
	Shropshire, Brittany, Normandy, Jersey, the Limousin, the Estrelles, Erzgebirge, G. of Bothnia, Sweden, Finland, Moravia.	
	Bala and Caradoc.	
IV.	**System of Morbihan** (Vannes, E. 38° 15′ S.)	E. 36° 35′ S.
	Brittany, Guernsey, Normandy, Russian Poland, ranges N. of Lake Superior, the Green Mountains, New Grenada.	
	Upper Silurian.	
V.	**System of Westmoreland and Hundsrück** (Bingerloch, E. 31° 30′ N.)	E. 41° 12′ N.
	Westmoreland, the Grampians, Leadhills, Anglesea, Isle of Man, Cornwall, the Eifel, the Hundsrück, the Hartz, the Pyrenees, the Vosges, Bohemia, Corsica, Ardennes, Cevennes, Sardinia.	
	Devonian.	
VI.	**System of the Ballons and of Calvados** (Ballons, E. 16° S.)	E. 6° 17′ S.
	The Vosges and Black Forest, Normandy, Charnwood Forest, the Pyrenees, the South Urals, the Hartz, Sweden, Central Russia.	
	Millstone-Grit.	
VII.	**System of Forez** (Loire), (the range of the Forez, N. 15° W.)	N. 21° 51′ W.
	The Loire, La Vendée, Ardêche, the Limousin, the Corbières, West coast of Scotland, South Sweden, Northern Urals.	
	Coal-Measures.	
VIII.	**System of the North of England** (Yoredale, N. 5° W.)	N. 7° 27′ W.
	The Pennine Chain, Malvern, Dudley, the Lickey Hills, Coalbrook Dale, West coast of Normandy, the Tarare Hills, Mount Maures (Var), the Eastern Alps, Corsica, the Islands of Gothland, and North-eastern Russia.	
	Permian (after the Zechstein).	
IX.	**System of the Netherlands and South Wales** (Mons, E. 5° N.) ...	E. 11° 54′ N.
	The Ardennes, Brittany, Westphalia, the Mendips, South Wales, the South of Ireland, North Staffordshire, Wexford, Cornwall, Saxony, Nassau, Poland, Donetz (South Russia), the Alleghany Mountains.	
	Lower New-Red-Sandstone [the Bunter Sandstone].	
X.	**System of the Rhine** (Strasbourg, N. 21° E.)	N. 11° 8′ E.
	The northern part of the Vosges and the Black Forest, the Alps, Northern Scandinavia.	
	Upper New-Red-Sandstone [the Keuper Marls].	
XI.	**System of Thüringerwald and the Morvan** (Mount Greifenberg, W. 39° N.)	W. 26° 22′ N.
	The Thüringerwald range, the Morvan, Ferques (Boulonnais), Co. Dublin and Cavan, Turkey, Greece, Nova Scotia, Northern parts of the United States of America.	
	Jurassic [Rhætic?].	
XII.	**System of Mount Pilas, of the Cote d'Or, and of the Erzgebirge** (Dijon, E. 40° N.)	N. 42° 27′ E.
	Burgundy, the mountains of Forêz and the Cevennes, the Pyrenees, Saxon Switzerland, the Middle Jura, Spain, the Western Altai, the Sierra Nevada (U.S.), and Uintah Mountains.	
	Cretaceous [Upper Greensand].	
XIII.	**System of Mount Viso** (French Alps) **and of Pindus** (Mount Viso, N. 22° 30′ W.)	N. 31° 55′ W.

	Orientation on the meridian of Milford Haven.
The Alps of Dauphiné and Nice, the Touraine, the South-west Jura, the Pindus range (Greece).	
Lower Eocene.	
XIV. **System of the Pyrenees** (the Peak of Nethou, W. 18°N.).	W. 14° 14′N.
The Maladetta Chain: the Central Appenines from Genoa to Ancona, the Julian Alps, the Pays de Bray (?), the Bas Boulonnais and the Weald, the Valley of Kingsclere, hill ranges in Bosnia, Candia, Greece, the Carpathians, the western Caucasus, Algeria, Tunis, Ghauts of Malabar.	
Upper Eocene. [*Lower Oligocene?*].	
XV. **System of Corsica and Sardinia** (Cape Corsica, N. and S.)	N. 11° 21′ W.
The islands of Corsica and Sardinia, the hills between the Allier and the Loire, Normandy, Somter-Merî (the Morea), hill ranges in Servia and Transylvania, Algeria, and the Lebanon.	
Fontainebleau Sands [*Middle Oligocene*].	
XVI. **System of the Isle of Wight and of Tatra** (Hungary, Mount Lomnica, E. 4° 50′ S.)	E. 14° 13′ N.
Isle of Wight, the Weald, Hungary, Artois, Illyrian Alps, the Brenner range, the Isle of Candia, Elba, the Lomont Jura, parts of the Alps and Pyrenees, the Hœmnis or Rilo-Dagh ranges (Turkey), Southern Greece, Algeria.	
Meulière de Montmorency [*Upper Oligocene?*].	
XVII. **System of the Sancerrois and Erymanthus** (Sancerre, E. 26°N.) ...	E. 31° 52′ N.
Sancerre (Cher), the Erymanthus range (Greece), the Black Mountains (Hérault), the islands of Crete and Cos, coast ranges of Asia Minor.	
Miocene [*the Faluns of Touraine*].	
XVIII. **System of the Western Alps** (the Alps of Dauphigny, N. 26° E.) ...	N. 18° 30′ E.
The Alpine ranges from Marseilles to Zurich, the Southern Jura, the Corbieres, various hill ranges in Sicily, Calabria, Tuscany, the Appuan Alps, the Scandinavian Alps, the Isle of Rhodes and the hills of the southern Crimea, some ranges in Asia Minor, Cape Bon (North Africa), Tunis.	
Pliocene.	
XIX. **System of the principal chain of the Alps** (the chain of Mont Blanc, E. 16° 25′ N.)	E. 23° 10′ N.
The range of the Alps between Savoy and the Tyrol, the Jura, parts of the north of France and Kent, the Sierra Nevada (Spain), the Balearic Islands, the coast ranges of South Italy and Sicily, Crete, the Eastern Balkans, Taurus, central Caucasus, central Algeria, Morocco, the lower Himalayas.	
Alpine Diluvium [*Quaternary*].	
XX. **System of Tenara** (Greece), **Etna, and Vesuvius** (Etna, N. 8° 21′ W.)	N. 26° 15′ W.
Lipari, Bohemia, northern Auvergne.	
Present period.	

In the foregoing list it rarely happens that the supplementary names are those of places on the same great circle of the sphere as the primary system, but on those of the smaller subsidiary circles parallel to the main great circle, where the effects of the primary system are of unequal importance.

In his last comprehensive work on this subject, M. Elie de Beaumont states that the number of recorded 'mountain-systems' in all parts of the world had increased to 95, but it was a question whether they were all distinct. He considered that they could not at all events be fewer than 60,

and that in a few years the numbers might reach 100 or more. The additional systems are as under.

System.	Direction.	Age.
1. **System of Mount Serrat** ... ... Barcelona, Mount Serrat.	N. 42° W.	In the middle of the Sub-Apennine (Pliocene) period.
2. **System of Mount Seny** ... ... Tarragona, Cape Gata.	N. 34° E.	Between the Lias and the Oolites.
3. **System of Mount Ventoux** ... ... Montpellier, Languedoc.	W. 36° S.	Between the 'Diluvium Alpin' and the recent Alluvium.
4. **System of the Valley of the Doubs** .. ... Besançon, Suabian Alps.	E. 30° 30′ N.	Between the Cornbrash and the Oxford clay.
5. **System of La Margeride** ... ... The mountains of the Cevennes.	N. 33° 15′ W.	Silurian, near the time of the Hundsrück system.
6. **System of the Vosges** ... ... The Vosges mountains.	N. 15° E.	Devonian, near the time of the Ballons system.
7. **System of the 'Marne' Faults** ... ... Buxières-lez-Belmont (Haute Marne).	S. 31° 15 E.	Date not determined. Comparatively recent?
8. **System of Erymanthus and the Mermoncha?** Mountains of Miliamah, Algeria.		Before the end of the Miocene; ante-Sahelian.
9. **System of the Nador** ... ... Algeria, Estramadura.	N. 30° W.	Approaches to the system of Mount Serrat.
10. **System Central of Madagascar**	N. 24° 30′ E.	Systems of Madagascar. Age not determined. Supposed to be an independent series, or related to some of the Asiatic systems.
11. **System of the Granite and Porphyries** ...	N. 3° W.	
12. **System of the Diorites** " ...	N. 48° 5′ W.	
13. **System of the N.W. Basaltic axis**	N. 42° 3′ E.	
14. **System of the N.E.** " "	N. 14° W.	
15.[1] **System of the Laurentian Mountains** . Quebec, Lake Superior.	E. 5° N.	Between the older crystalline schists and the Cambrian.
16. **System of the Two Mountains and Montmerency**	E. 40° N.	End of Lower Silurian.
17. **System of Montreal**	E. and W.	Subsequent to the Trenton series (Lower Silurian).
18. **System of the Catskill Mountains**	E. 15° S.	Subsequent to Devonian.
19. **System of the Sierra Mogollon** (New Mexico) Sources of the Rio-Gila and Rio-Brieta.	N. 60° W.	Subsequent to the Trias.
20. **System of the Rocky Mountains and of the Sierra Madre** (Mexico)	none given.	Subsequent to the Cretaceous strata.
21. **System of the Coast Range of California** ...	N.N.W. to S.S.E.	Not given.
22. **System of the Sierra Nevada** (California) ...	N. to S.	Between the Eocene and Quaternary periods.
23. **System of the Sierra of St. Francisco and of Mount Taylor**	E. & W. & N. & S.	Forms two volcanic bands at end of the Quaternary period.
24. **System of Central America** ... ... The volcanoes of Tolima and Orizaba. ...	W. 35° N.	Coincides with a line of great volcanoes.
25. **System of Segovia** ... ... Cosequina and Cape Gracia-a-Dios.	E. 15° 20′ N.	Corresponds with great mineral and porphyritic lines of eruption.

[1] The American Systems, Nos. 15 to 23, are on the authority of M. Jules Marcou.

System.	Direction.	Age.
26. **System of Venezuela and the Volcanoes of Mexico**	E. and W.	Recent, though the volcanoes of Mexico may be on old lines of fracture.
27. **System of Meridional Central America** ... Valleys and mountains of Central America.	nearly N. and S.	Geologically recent.
28. **System of Hundsrück of South America** ... Chili and Brazil.	N.E. and S.W.	Silurian, near the time of the Hundsrück system.
29. **System of the Cordilleras of Nahuebouta** ... Southern Chili.	N. 26° 20′ E.	Post-Devonian.
30 **System of Western Chili**	N. 8° 30′ W.	Subsequent to the Red Sandstone of the country.
31. **System of the Transverse Chains** ... ... Concepcion and Coquimbo.	E. 6° 10′ N.	Between the Neocomian and Cretaceous.
32. **System of the Principal Andes** ... ... The Cordilleras of Chili.	N. 8° 30′ E.	Subsequent to the lacustrine and marine Tertiaries of Chili and Bolivia.
33. **System of Mont Notre Dame, Canada** ...	E. 20° N.	May belong to the system of Morbihan.
34. **System of the Green Mountains, U.S.A.** ...	N. 7° E.	Subsequent to the Upper Silurian.
35. **System of the Alleghanies and M. Ozarks** ...	N.E. and S.W.	Subsequent to the Coal Measures.
36. **System of Brazil**	E. 38° N.	Archæan?
37. **System of the Pampas**	E. 25° 30′ S.	No date given.
38. **System of Itacolumi**	E. and W.	Between Carboniferous and Red Sandstone strata.
39. **System of the Eastern chain of the Andes** ...	N.W. to S.E.	No date given.

NOTE.—It is possible that in this last list some of the systems, which are given by different observers, are repeated. Each system has here its own local orientation without reference to any common meridian. Some appear as subordinates in the first list.

In the last list the lines of disturbance include not only mountain-ranges, but also great lines of fracture, whether represented by faults, by dykes of igneous rocks, or by mineral veins. In Europe the lines of great faults and mineral veins are also considered by Elie de Beaumont to coincide with the direction of the several mountain-chains or axial lines of disturbance.

The several Epochs of Disturbance of the principal Mountain Ranges. The upheavals of the various great mountain-chains of Europe were ultimately referred by M. de Beaumont to various geological periods, although, as before said, he believed their marked features at the present day to have been given by one dominant disturbance at one particular time—an opinion which has very commonly led to the belief that the eminent author attributed the origin of each mountain-range, and of each of its parallel chains, to one single upheaval—and that he held all upheavals to have been sudden. This, however, is not a necessity of the hypothesis, and we may within certain limits consider the upheavals, not only to have been successive, but also slow and prolonged, though not free from occasional paroxysmic action.

With the multiplicity of systems, and their frequently near parallelism, the difficulty of distinguishing between their respective orientations increases; and as the lines of fracture are also lines of least resistance, there is a possibility, where this near parallelism exists, of one line of disturbance having been diverted from its course by confluence with a pre-existing line. Elie de Beaumont compared the recurrence of systems on the same lines, in some respects, to the isomorphism of minerals of different composition, and considered that, like them, they form exceptional cases.

The space at our disposal will not allow me to enter more fully on the extension and relations of the several mountain-systems; but, combining Elie de Beaumont's researches with the observations of other geologists, we may attempt to trace the history and growth of some of the more important mountain-ranges in England and other parts of the world, and note the periods of the greater deformations of the earth's crust. The reader will remember that the older ranges must in the long course of time have lost much of their prominence by denudation or by enclosure within newer strata.

They may be divided into—

Ranges of Archaean and Lower Palaeozoic Date. The oldest lines of disturbances in Britain are those by which the Laurentian and Pre-Cambrian rocks were crushed, contorted, and upheaved before the deposition of the Cambrian strata. Murchison states that the strike of the highly inclined and folded gneiss rocks of this age in Ross-shire is N.N.W. to S.S.E., which corresponds with that of M. de Beaumont's 'System of La Vendée;' but the Dimetian rocks of Pembrokeshire strike, according to Dr. Hicks, N.W. and S.E. The strike again of the Pebidian rocks, which is E.N.E. and W.S.W., agrees with that of the 'System of Finisterre.'

FIG. 159. *Section of the Cambrian Rocks of Ross-shire resting unconformably on Laurentian Gneiss.* (Murchison.)

The coincidence of strike and the extent of the parallel flexures in the Laurentian rocks over very large areas are interesting features. The same fact of a nearly common strike over wide regions has also been remarked upon by the American geologists with reference to the Archæan rocks of the United States and Canada.

The long series of the Cambrian and Lower Silurian strata succeed one another in the Welsh area with evidence of great oscillations, but with little or no evidence of greater disturbance, for there is no marked unconformity of the strata until we reach the May Hill sandstone; and even this

period does not seem marked in Wales by the elevation of any great mountain-range, though M. de Beaumont places 'the System of the Longmynd' at a period anterior to the Caradoc epoch. This part of Wales is, however, so much disturbed, and the strike so local, that Mr. Hopkins considered that the older systems there could not be determined with any certainty, and admitted of no independent proof of age.

That there was an important break, at all events, between the Longmynd rocks and the Upper Silurian is very apparent in the following section.

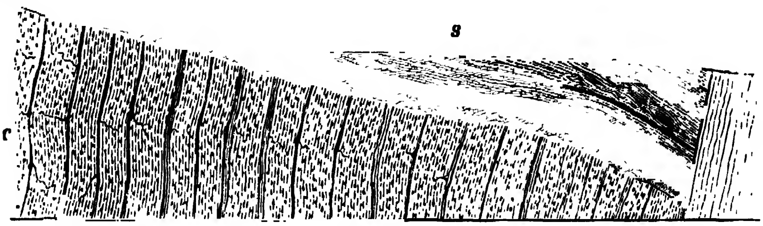

FIG. 160. *Section on the slope of the Longmynds near Church Stretton.* (Geol. Survey.) *c.* Cambrian strata; *s.* Upper Silurian strata.

In America not only do unaltered Upper Silurian strata overlie unconformably Lower Silurian slates, but great ranges of mountains, extending from Lake Erie into Tennessee, including the Green Mountains and the Taconic range[1], which rise to the height of 3600 feet, were uplifted and emerged at an inter-Silurian period.

Professor Sedgwick[2] has shown that, subsequent to the Upper Silurian and before the Devonian period, the mountain-ranges of Westmoreland, some districts in the south of Scotland, and parts of Wales were raised—all the Silurian strata being disturbed, and the Old Red Sandstone resting unconformably on their upturned edges (Fig. 161). It is evident that a very marked unconformity, indicative of a wide-spread disturbance, exists not

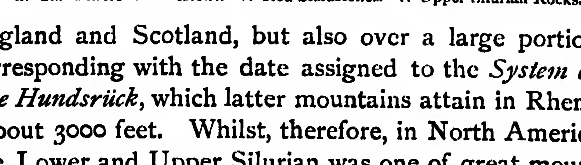

FIG. 161. *Section across Whinfell, Westmoreland.* (Geol. Survey, ¼.) *a.* Carboniferous Limestone. *b.* Red Sandstones. *c.* Upper Silurian Rocks.

only in England and Scotland, but also over a large portion of Central Europe, corresponding with the date assigned to the *System of Westmoreland and the Hundsrück*, which latter mountains attain in Rhenish Bavaria a height of about 3000 feet. Whilst, therefore, in North America the period between the Lower and Upper Silurian was one of great mountain disturb-

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[1] Dana's 'Manual,' p. 212.

[2] 'Trans. Geol. Soc.,' 2nd ser., vol. iv. p. 47.

ance, and is but little marked in Europe, except in the west of Ireland, it is just the reverse with respect to the period between the Silurian and Devonian, which in the European area was marked by great upliftings and disturbances, whereas in North America there is an easy transition from the Upper Silurian to the Lower Devonian.

On the other hand, in Europe there does not appear to have been any great disturbance between the Devonian and Carboniferous periods. There were oscillations and changes of level; but, as a rule, there is little or no unconformity between the Upper Devonian and Lower Carboniferous strata. In America there is a more marked unconformity.

Carboniferous Period. Nor is there any appearance of marked disturbance in this country between the period of the Carboniferous Limestone and the Millstone-grit, these strata succeeding conformably and passing up into the Coal-measures. On these grounds, Mr. Hopkins objected to the introduction of '*the System of the Ballons of the Vosges*.' In many cases, however, formations at a distance from the centre of disturbance succeed one another without apparent unconformity or with an unconformity marked only by a gradual overlap, and yet are found to be in marked discordance along a line of greater axial disturbance. At all events, it is clear that, whereas the Carboniferous Limestone indicates open seas of some depth with a distance from land, the Millstone-grit shows in its conglomerates and mineral characters the proximity of coasts and of granitic lands. It was a period of emergence over large areas, and, according to M. Elie de Beaumont, of mountain-disturbance in some parts of Europe. He also refers to this period in America the elevation of part of the Alleghany mountains; but American geologists have shown that the period of their great disturbance was at the close of the Palæozoic period, and that the period of the Millstone-grit was one only of emergence, or of a great upward movement which ushered in the subsequent period of subsidence of the Coal-measures. There seems to be, therefore, no evidence in England or America of much more than steady oscillation during these periods. At the same time it is quite possible that there were greater axial disturbances at a distance, and that important faulting of the strata may have been produced in this country by such upheavals as those which, according to Elie de Beaumont, marked the *Systems of the Ballons and of Forez* in the Vosges, Sweden, and elsewhere on the continent.

Permian and Triassic Periods. A very well-defined upheaval took place in this part of Europe at the close of the Carboniferous period. The Pennine hills—that well-known high range of Mountain limestone which trends N. and S. from the borders of Scotland to Derbyshire—were raised between the Coal-measures and Permian periods.

The unconformity is strongly marked in the relative position of the Coal-measures and of the overlying Permian strata on both sides of the broad

Pennine chain, in Durham and Yorkshire, where Permian strata cover unconformably Carboniferous rocks, as in the following section.

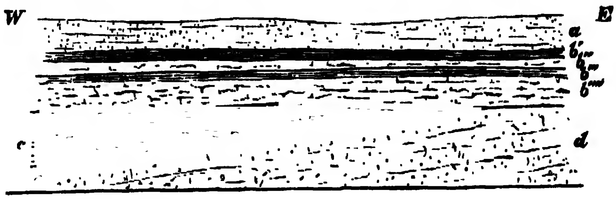


FIG. 162. *Section showing the position of the Coal-measures near Appleton, Yorkshire.* (Reduced from the Geol. Survey.)

a. New Red Sandstone (Bunter).
b'. Upper Marl }
b''. Upper Limestone } Permian.
b'''. Middle Marl }
b''''. Lower Magnesian Limestone }
c. Coal-measures.
d. Millstone Grit.

The range of the Malvern hills forms another parallel ridge of the same age, running nearly due N. and S., and also anterior to the Permian and New Red Sandstones which abut against the older rocks (Fig. 163). The railway sections through these hills well show the extent to which the Silurian and Devonian strata have been affected by this line of disturbance[1].

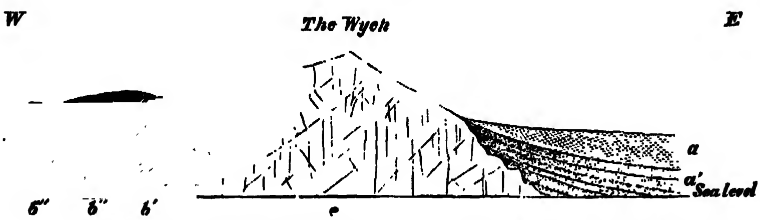


FIG. 163. *Section across the Malvern Hills near Little Malvern.* (Geol. Survey, ⅛.)

b. Silurian. { *b'''.* Wenlock Series. *b''.* Woolhope Series. *b.* May Hill Sandstones. }
e. Syenite.
a, a'. New Red Marls and Sandstones.

Though this was not a period of such great upheavals on the continent of Europe as the one next succeeding, it has left its mark in the mountains of the Maures in the south-east of France, as well as in Corsica, and Northern Russia. In North America there is an absence of any marked disturbances,—the Permian strata there being continuous on the Carboniferous without interruption or unconformity, so much so that they have been placed by the American geologists in the upper division of the Carboniferous series.

Not so with the next *system, that of the Netherlands and South Wales*, when a large part of Northern Europe and of North America was disturbed and great mountain-ranges upraised. The effects of this disturbance are strongly marked in the Mendips—a range of hills running nearly

[1] The Rev. W. S. Symonds, 'On the Sections of the Malvern and Ledbury Tunnels, etc.'; 'Quart. Journ. Geol. Soc.,' vol. xvii. p. 152.

due east and west. The New Red Sandstone abuts against the southern flanks of this range, whilst on the northern side the Lias and New Red Sandstone rest unconformably on the disturbed Carboniferous rocks. This unconformity is very conspicuous throughout Gloucestershire (Fig. 164).

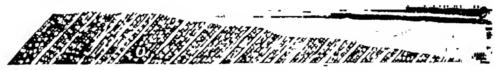


FIG. 164. *Section of the Lias (e) and New Red Sandstone (f) resting unconformably on the Carboniferous Limestone (m) and Old Red Sandstone (o), near Wapley, Gloucestershire.* (Geol. Survey, $\frac{3}{8}$.)

From Somerset this line extends westwards, tilting up the Carboniferous strata in South Wales and the South of Ireland; while eastward the old ridge passes under the Secondary and Tertiary strata of the south of England, and reappears on the surface in the Ardennes of France and Belgium, and continues thence to Westphalia, forming either a main axis or a series of parallel axes of elevation, extending in a somewhat irregular line for a distance of about 900 miles. A remarkable feature of this line of disturbance is the extreme contortion and inversion which the strata have undergone. This has been proved in the coalfields on the flanks of the Ardennes and of the Mendips in a way that would have been impossible without coal-workings. In Westphalia, where there has been less compression, the disturbance is exhibited in a series of folds. (See Sects. 1, 2, and 3, p. 260.)

Disturbances of this period affect some of the rocks in Nassau, in Poland, and in the south of Russia. In North America they are as important, and as strikingly mark the close of the Palæozoic period, as in Europe. All the Appalachian regions south-west of the Green Mountains were embraced in these movements, and the Alleghany Mountains are among the grand results[1]. The Coal-measures of Pennsylvania and Nova Scotia were tilted at various angles, doubled up into great folds, and fractured and faulted on a large scale; the strata were also inverted, and coal has been worked under Lower Silurian strata, as it has been under Devonian strata in the north of France and Belgium. The Alleghanies form a range from 30 to 40 miles wide, and rise in places to the height of 6000 to 6607 feet; not only they, but also the whole of the continental border from Newfoundland to Alabama, participated in these vast movements. If I understand M. Elie de Beaumont rightly, he refers this great upheaval of the Alleghanies to his *System of the Ballons;* but from the facts just stated, it would rather appear to have been of the same date as *the System of the Netherlands and South Wales.* As a consequence of this disturbance, the Jurassic rocks are commonly found lying in strong unconformity upon the Upper Palæozoic strata.

[1] Dana's *op. cit.* p. 395.

The way in which the three upper members of the Palæozoic series have been successively disturbed and placed in unconformable superposition one to the other, while the Trias succeeds in undisturbed overlap, is well illustrated in the following illustrative section.

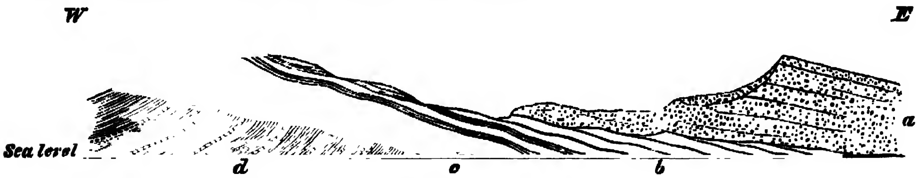


FIG. 165. *Section across the south end of the Coalbrook Dale Coalfield near Bridgnorth.* (Reduced from Geol. Survey.) *a.* New Red Sandstone. *b.* Permian. *c.* Coal Measures. *d.* Old Red Sandstone (Devonian).

Ranges of Mesozoic Date. In Europe during the Mesozoic period there were frequent great continental movements, though but few sharp lines of mountain upheavals, unless during Triassic times. The *System of the Rhine*, which is of the age of the Muschelkalk, clevated the northern part of the Vosges mountains and the Kyolen range,—a range in the north of Scandinavia rising to the height of 5956 feet. This system has, according to M. de Beaumont, left only a few traces in Britain.

The next disturbance, intermediate between the Trias and Lias, was one of more importance, having resulted in the uplifting of the Thüringerwald range in Central Germany—a range extending for a distance of 50 miles and rising to a height of 3500 feet. The Morvan, a granitic range in Eastern France, is likewise of this age. Some of the mountain-chains of Turkey and Greece are also considered to be of contemporary age. In North America, from Nova Scotia to South Carolina, this seems to have been a period of abundant trap-dyke eruptions, but not of the forming of any great mountain-chain.

Jurassic Period. The successive Liassic and Oolitic periods do not appear to be marked in Europe by the upheaval of any mountain-chain unless it be by the chain of Mount Seny, which extends from near Barcelona to the south-east coast of Spain.

Cretaceous Period. At the close, however, of the last period, and before the deposition of the Lower Cretaceous strata, a continental movement of great importance, accompanied by the elevation of several mountain chains (*System of Mont Pilas and the Erzgebirge*) in continental Europe, took place. It was at this period that that part of the Cevennes mountains, of which Mont Pilas forms the culminating point (3517 feet), was uplifted. The mountains of the Erzgebirge, a range of South Germany, about 120 miles long and 25 miles wide, and from 2500 to 4590 feet high, together with the chain of the Middle Jura, and some of the chains of the Ural and the Altaï, were likewise uplifted at this time.

In England this period is marked by a great stratigraphical break,

and by the transgressive spread of the Cretaceous strata successively over the slightly upturned edges of the Oolitic, Liassic, and Triassic series, showing these strata to have been elevated and denuded before the deposition over them of the horizontal Cretaceous beds (Fig. 114, p. 251). It is to this time that M. de Beaumont refers the long low uplift which raised the Lias, with its overhanging Oolitic escarpment, from the Cotswolds to the north of Lincolnshire, though not of course in their present denuded form.

The area of greatest disturbance at this period was, however, that of the Pacific coast of North America. While in that area no unconformity has been observed in the Triassic and the Jurassic series, the close of the Jurassic period was, on the west of the Rocky Mountains, the epoch of some of the grandest disturbances of the earth's surface. They resulted in the upheaval of the Sierra Nevada, the Humboldt ranges, and the Wahsatch and the Uintah mountains,—ranges which extend for a length of more than 400 miles and rise to the height of 15,000 feet.

Ranges of Tertiary Date. It is very remarkable that the great stratigraphical and palæontological break between the Chalk and the Tertiary series finds no expression in any important physical features of the surface. There is evidence of vast slow continental elevation and of extensive denudation, but the period is not marked, either in Europe or in North America, by the uplifting of any great mountain-range. The great disturbing forces of Middle Eocene time may, however, have been in slow general operation through the Cretaceous period, and have culminated in axial uplifts only during the Eocene period.

The oldest Tertiary mountains are those of the *System of Mount-Viso*, one of the peaks of the Alps of Dauphiné, which rise to the height of 13,599 feet. The south-west Jura, and the range of the Pindus (8950 feet) in Thessaly, are of the same age.

It is to disturbances of Tertiary date that is due the final touch to the proportions of some of the loftiest mountain-ranges in the world. Great interest attaches to these mountains owing to the completeness with which their structure has in many cases been determined, and which enables us to follow their history in more detail, and to show that although it is convenient to assign the geological age of the range to the dominant uplift, older movements can, in these instances, as in others, be traced back to periods long anterior to that of the last main upheaval.

The Pyrenean Periods. These mountains have a granitic axis to which succeed crystalline schists referred to Laurentian age. These are overlain, apparently conformably, by Cambrian, Silurian, and Devonian rocks. According to M. Magnan[1], a first disturbance then took place when the older Palæozoic rocks were raised and denuded. On the upturned edges of these rocks Carboniferous conglomerates and sandstones

[1] 'Mém. Soc. Géol. de France,' 2nd sér., vol. x. p. 1-111.

rest unconformably. Then follow, in conformable sequence, strata of Permian, Triassic, Jurassic, and Lower Cretaceous age, the last of these being developed on a very grand scale. Another great break then occurs; and conglomerates of the age of the Upper Greensand and the Chloritic Marl are spread unconformably over the older rocks. To these succeed conformably the Upper Chalk, the Garumnian Chalk (a fluvio-marine equivalent of the Danian), and the lower and upper (Oligocene?) Eocene. It was then that the great axial upheaval of these mountains took place and Nummulitic strata of Eocene age were tilted, folded, and raised to the height of 11,000 feet, or to within 200 feet of the highest summit of the Pyrenees.

Against these upraised strata conglomerates and marls of Miocene age range in horizontal beds. Later disturbances, however, took place on the Lower Pyrenean range of the Corbières, for there these Miocene beds have been disturbed and denuded and covered unconformably by beds of Pliocene age. There are thus four well-marked periods of major disturbances; and, taking into account the minor movements to which these mountains have been subject, it is estimated that, on the whole, seven periods of disturbance have participated in the elevation of this great mountain-range.

Amongst other mountain-ranges of this date are the central chain of the Apennines, parts of the Carpathians, part of the Western Caucasus, of the Maritime Alps, and of some chains in the N.E. of Mesopotamia and along the Persian Gulf.

It is to this period that the elevation of the Weald has been referred. It may have began then, and the planing down of its summit-level may then have commenced; but its main elevation and subsequent denudation must have been of later date—a date subsequent to the deposition of the Lenham sands, which are of Pliocene age.

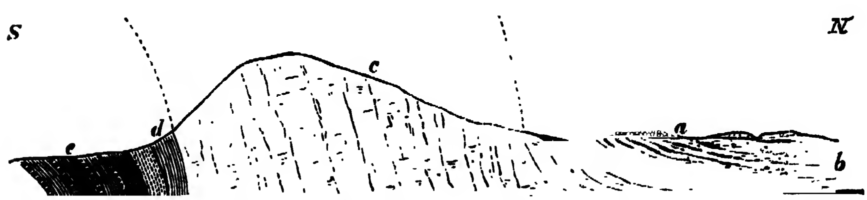


FIG. 166. *Section across the centre of the Isle of Wight.*
a. Quaternary Gravel. *b.* Tertiary Strata. *c.* Chalk. *d, e.* Lower Cretaceous and Neocomian Strata.

The only other marked line of disturbance of Tertiary age in England is that which has thrown up the central chalk ridge of the Isle of Wight and Purbeck; but, although we know it to be subsequent to the Eocene and Oligocene strata of the Isle of Wight, which it has tilted into vertical

positions, there is nothing to fix its upper limits. We only know that it is pre-Quaternary, for drift-beds of that age overlie horizontally the disturbed Tertiary strata in White Cliff Bay and elsewhere in the Island.

The Jura. The first disturbances of the Jura mountains date from the Secondary period, though the dominant upheaval took place, as in the Pyrenees, in Tertiary times. These mountains are formed by a succession of massive parallel flexures of Jurassic strata overlying Triassic beds, and underlying Cretaceous and Tertiary strata, of which isolated portions are found in places in the synclinal folds and on the anticlinal ridges of the range, showing that all these strata participated in the upheaval to which the present 'relief' of this chain is due. The summit-levels are divided by longitudinal valleys, which are generally lines of great faults, running parallel to the massive folds or separate ridges.

It would seem that the main fracturing and dislocation of the rocks of the Jura took place at the same time as the great upheaval of the Alps, namely, after the deposition of the Pliocene beds of Œningen.

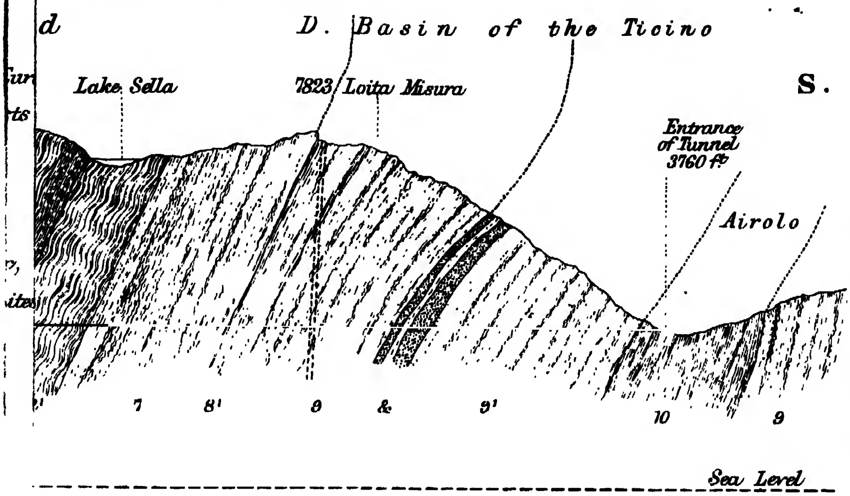
The Jura presents another instance of a curved range, varying as much as 20° to 30° from a straight line, and there is nothing, according to M. Thurmann, to indicate that it is formed of chains of separate dates, but that, on the contrary, the several chains are of common and synchronous origin [1]. The anticlines bend over towards the French side of the Jura, showing that there has been a lateral thrust from the Swiss or Alpine side. The sections and tunnels of the railways across the Jura have greatly assisted geologists in determining with much accuracy the character of the disturbances which have affected this mountain range [2].

The Alpine Periods. The massif of the Alps is closely linked in its origin to that of the Jura. The elevation of this grand chain is ascribed to three main systems of disturbance—spread over a long period of time, but acquiring their maximum development during the later geological times. The ground from Savoy to Austria began apparently to be an area of disturbance and upheaval towards the end of the Palæozoic period, when the crystalline schists and Carboniferous strata were raised and formed a land, round which Permian conglomerates were deposited. Subsequently successive subsidences and local fractures and movements of oscillation occurred, probably during Rhætic times, while to the strata of that age a long series of Oolitic and Cretaceous deposits succeed conformably. Towards the close of the latter period a fresh upheaval took place along the present line of the Alps—an upheaval prolonged into Eocene times. But it was after the period of the Molasse (Miocene) that the greater disturbance and upheaval took place, and the Western Alps assumed

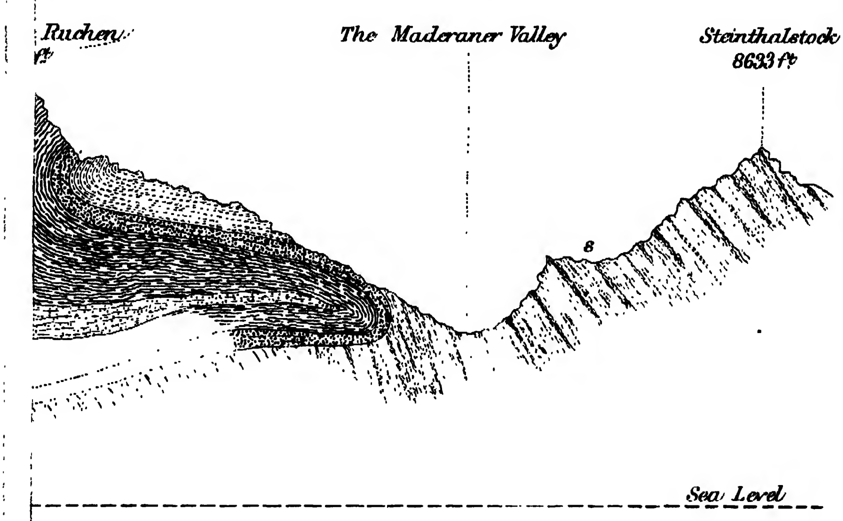
[1] 'Bull. Soc. Géol. France,' 2nde sér., vol. ii. p. 47.

[2] Desor, 'Les Tunnels du Jura;' 'Sur le Jura Neufchâtelois.'

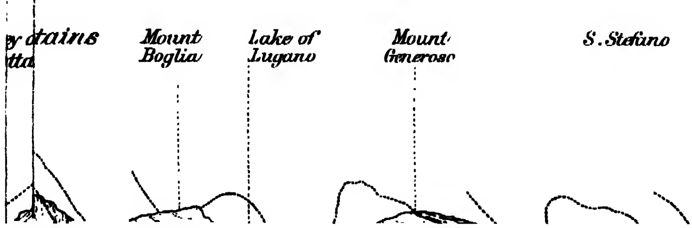
MILES (AFTER STAPFF)



NE TO NEAR THE BRUNNI PASS (HEIM)



IN PART)



their present status. The other grand movement, which raised the principal chain of the Alps,—or that of Mont Blanc,—was placed by M. de Beaumont so late as the Post-Pliocene period, if not to the time of the 'Diluvium Alpin' (Glacial). But the Swiss geologists generally question this conclusion, and consider that the conglomerates supposed to be of Quaternary are really of Pliocene age. Some geologists further doubt whether the last great elevation of both these chains of the Alps should not be referred to one date. Altogether, however, no fewer than five systems of elevation are supposed to have co-operated in the formation of the Alps.

While the range of the Jura exhibits great rolls and flexures, and but comparatively little compression, the Alps exhibit the most intense compression and the most marvellous inversions of the strata, accompanied by enormous faulting. No other range of mountains has been the subject of so much study as the Alps[1]. The admirable descriptions and sections of the Swiss geologists especially should be studied by every Alpine student; but the structure is so complicated that much yet remains to be done. Even as to the extent of faulting there are wide differences of opinion; while some geologists introduce great faults to explain the extraordinary conformation and the discordant levels of rocks of different ages, Heim[2], in his finished and elaborate sections, relies chiefly on inversions (see Sects. 2 and 3).

Thanks to the carefully made section of the St. Gothard Tunnel by Stapff (Sect. 1), geologists are now furnished with exact details of the structure of the central axis of the Alps. This centre, combined with the sections made by Favre and Heim of the other parts of the range on the Swiss side, and of Taramelli on the Italian side of the Alps, gives a consistent picture of the whole breadth of that great European chain, such as is represented in Section 3 of the same Plate.

The Himalayan Periods. The colossal range of the Himalayas has been described by Sir Richard Strachey[3]; and more recently Messrs. Medlicott and Blanford have given a very interesting history of this vast chain. They show that in these mountains we have a wonderful instance of the growth of a range commencing in Palæozoic times, renewed in Tertiary times, and even prolonged, in their opinion, to the present day; they consider it possible that the process of elevation in these the highest mountains in the world is still going on, although proceeding at a very slow rate, but nevertheless to an extent sufficient to counterbalance the effects of denudation[4].

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[1] For structural descriptions of the Alps, see also Sedgwick's and Murchison's paper in 'Trans. Geol. Soc.,' 2nd ser., vol. iii; Murchison's paper in 'Quart. Journ. Geol. Soc.,' vol. v. p. 157; and various papers by Studer, Escher von der Linth, Favre, Renevier, Lory, Heim, and others.

[2] 'Mechanismus der Gebirgsbildung,' etc.

[3] 'Quart. Journ. Geol. Soc.,' vol. vii. p. 292, and vol. x. p. 249.

[4] 'The Geology of India,' published by order of the Government, Calcutta, 1879, pp. lvii, 571, and 620.

The axis of the Himalayas consists of gneissic rocks of two ages, of which the upper one passes up into Silurian slates and contains fragments of the older gneiss. To these succeed rocks probably of Carboniferous age, upon which repose fossiliferous Triassic strata. Lower ridges, running parallel with the main axis, consist in places of Cretaceous strata; but more generally thick masses of nummulitic Eocene strata succeed the older rocks, while the sub-Himalayan ranges are formed of Upper-Miocene and Pliocene strata. There are also a set of high-level gravels, which are probably of early Pleistocene age, capping low hills at an elevation of 500 to 600 feet above the adjacent rivers,—2000 to 3000 feet above the sea-level,—and resting upon the edges of vertical Siwalik conglomerates of Pliocene date.

These mountains form a number of great ridges, having a general W.N.W.-E.S.E. direction, but with so many variations in the strike that range makes a long curve facing southwards.

A considerable elevation of Palæozoic rocks took place in the Himalayan area in Pre-Tertiary times; but this elevation was in the form of a simple protuberance, and was not accompanied by compression and contortion of the strata. Messrs. Medlicott and Blanford think that the whole of the gigantic forces to which the contortion and folding of the ranges of the Himalayas (together with others of the extra-peninsular mountains) are due, must have been exerted after *Eocene* times; while in the sub-Himalayan range a great amount of disturbance is of Post-pliocene date, and in some of the lower chains even the principal disturbance is of that date. The conclusion is that the actual direction of all the Himalayan chains is clearly due to Post-Eocene lines of disturbance.

The Andesian Periods. In the great South-American range of the Andes we have another instance in which the features of great age and recent growth are strikingly combined. These mountains, like most of the other mountain-ranges of the world, consist of several parallel or nearly parallel chains, more or less independent one of another. According to the late David Forbes[1], the Quaternary deposits of the coast are succeeded by ranges of Oolitic age, overlying Permian or Triassic strata, while the great central ridges consist of Devonian and Silurian strata. On the eastern sides of the range, metamorphic, and, in places granitic, rocks appear. The whole series is penetrated by porphyritic and volcanic rocks of various dates.

M. Pissis[2] considers that there have been four periods of upheaval. The earliest of these—his *System of the western chain of Chili*—took place after the deposition of the red sandstones of Permian or Triassic age, which

[1] 'Quart. Journ. Geol. Soc.,' vol. xvii. p. 7.
[2] 'Ann. des Mines,' 5me sér., vol. ix. p. 81, 1856.

are overlain unconformably by conglomerates, limestones, and saliferous marls of Oolitic or Cretaceous age; while these have been disturbed by the later *System of the transverse chains*. The latter rocks are succeeded by marine and lacustrine beds of Tertiary age; and it was after the deposition of these that the great upheaval (*System of the principal chain of the Andes*) took place. This disturbance was accompanied by vast outpourings of andesites and by great parallel lines of fault.

Here and there resting on these strata unconformably are local beds of sand and gravel (with recent shells) of Quaternary age, which range from the coast to the first range of hills, the beds becoming coarser as they approach the hills. These beds are in general at levels of from 25 to 500 feet, and run for some distance up the valleys inland. D'Orbigny found recent shells and bones up to heights of 300 feet; and Darwin mentions an instance in which Balani were found adhering to a rock about 400 feet above the sea-level. The greatest height noticed by Darwin at which such remains occurred was 1300 feet in the neighbourhood of Valparaiso [1].

This upheaval is termed by M. Pissis the *System of Chili*; but he states that, although it has increased the absolute height of the Andes, it has not increased their relative importance. It seems in fact to have been one of those great continental movements 'en masse,' rather than the axial and ridge-making lines of disturbance to which mountain-ranges owe their origin.

In Brazil and Bolivia M. Pissis found evidence of an upheaval which preceded all the above—one which in early Palæozoic times raised a chain of low hills of granitic rocks and of talcose schists of Silurian age; and these he thinks might have shadowed out the land along which subsequently rose the great ranges of the west coast of South America, though it was not until Tertiary times that the forces which raised the vast range of the Andes reached their culminating point. There is thus exhibited here, as in the Himalayas, evidence that the elevatory forces, which commenced in early geological times, continued in action through the succeeding Secondary and Tertiary periods down to the period when Indian man existed on the coast, and which have, even at the present day, not altogether ceased their occasional spasmodic exhibition.

Neither in the case of the Andes nor of the Himalayas are the physical details sufficiently well known to obtain an accurate section of the interior structure of those great ranges.

[1] 'Geological Observations in South America,' pp. 47 and 49.

CHAPTER XVIII.

METALLIFEROUS DEPOSITS.

MINERAL VEINS. FISSURE- AND FAULT-VEINS. THE LODES AND ELVANS OF CORNWALL: THEIR WIDTH; DEPTH; AND LENGTH. CONTENTS OF THE VEINS. ORDINARY AND 'COMBED' VEINS. EXTRANEOUS BODIES IN VEINS. CAVITIES IN VEINS. SLICKENSIDES. SLIDES. AGE OF THE CORNISH LODES. THEIR STRIKE, INTERFERENCE, AND THROW. VEINS IN LIMESTONE; THE MINERAL VEINS OF CUMBERLAND, DERBYSHIRE, AND WALES. QUARTZ VEINS. OTHER FORM OF LODES; FLATS; FLOORS. MINERAL VEINS OF FRANCE; GERMANY; TRANSYLVANIA; SPAIN; NORTH AMERICA; MEXICO; SOUTH AMERICA; AUSTRALIA. ABNORMAL CONDITIONS; STOCKWERKS; FAHLBANDS. AGES OF MINERAL VEINS. PERIODS OF DISTURBANCE.

Mineral Veins. Faults and mineral veins are closely related. They are both due to disturbance and fracture of the earth's crust; but, whereas faults, as usually understood, are always accompanied by displacement of level, and generally by lateral compression, mineral veins are as frequently more or less open rents with little or no dislocation or compression. They form the two extremes of a series between which there is so gradual a passage that it is not possible to draw a line of demarcation. Ordinary faults contain, however, only local wall-débris, to the exclusion of all extraneous matter; while mineral veins, though mixed in most cases with variable proportions of rock-rubble from the enclosing walls, generally consist in great part, and often wholly, of introduced foreign mineral matter. One extreme constitutes 'fault-veins,' which merge, under the conditions above referred to, into 'fissure-veins.'

In either case they have this in common, that the introduced extraneous mineral substances are of the similar characters; although they are much more abundant and varied in the fissure- than in the fault-veins. These introduced mineral substances, which form with the wall débris the 'gangue' or veinstone of the lodes, consist in their relative order of abundance of—

1. *Quartz*—drusy, crystalline or chalcedonic, translucent, opaque, white,—with numerous vapour and water-inclusions; rock-crystals frequently line cavities and geodes in the vein.

2. *Carbonate of lime*—crystalline and crystallised in a variety of forms.

3. *Fluor-spar*—massive crystalline, or in cubical crystals, of various shades of white, blue, red, violet, etc.

4. *Sulphate of barytes*—massive and crystallised.

5. *Carbonates of barytes, strontian, magnesia* (pearl-spar), and *iron* (chalybite),—crystalline and crystallised.

Some one or more of these minerals always constitute the gangue, or matrix, as it were, through which are irregularly dispersed the various metallic ores. These latter consist, according to depth, age, and to the nature of the enclosing rocks, of native gold, silver, copper, etc.; or of the oxides or carbonates of iron, copper, silver, tin, etc.; or of the sulphides of lead, zinc, copper, antimony, iron, silver, arsenic, and a few other metals in smaller proportions (*ante*, Table, pp. 8, 9).

The metallic ores occupy relatively but a small proportion of a vein. They occur in masses, nodules, plates, and strings—thinning out or enlarging in a very capricious manner. In the case of the commoner metals it is necessary that the proportions should be comparatively large for the working to be remunerative; while for the precious metals very small proportions suffice. It has been estimated that, for profitable returns, the metal should be present in quantities not less than—for iron $\frac{1}{3}$rd, lead $\frac{1}{20}$th, zinc $\frac{1}{30}$th, copper $\frac{1}{50}$th, silver $\frac{1}{1000}$th, gold $\frac{1}{10000}$th; but these numbers will vary with different and improved modes of extraction, site, facility of access, etc. Although the great bulk of both gangue and ore form amorphous or crystalline masses, separate and perfect crystals of all the several minerals and ores occur, at places, lining the cavities, geodes, and fissures, which are of common occurrence in the veins.

Fissure- and Fault-Veins. For the convenience of description, mineral veins may be divided into fissure-veins, fault-veins, and (as a further and subordinate subdivision) quartz-veins. But it must be understood that they are all modifications of one general phenomenon connected with lines and centres of disturbance; the great physical questions connected therewith being one of the main points of interest to the geologist. The strike and range of the veins, their relation to disturbed districts and mountain-chains, and to questions of metamorphism, require therefore to be carefully noted; and it is for these reasons that I dwell on the subject longer than is usual in general treatises[1].

As types of *fissure-veins* we may take the great mineral-lodes of Cornwall and Freiberg; and of *fault-veins*, the lead-lodes of Cumberland, Derbyshire, and Wales.

The Mineral Veins of Cornwall[2]. These veins, like ordinary faults, do not hold a true rectilinear course, although they hold a general

[1] The special works on the subject to be consulted are Fournet's 'Sur les Filons Métallifères'; Burat's 'Minéraux utiles'; Moissonet's 'Lodes of Cornwall'; Whitney's 'The Metallic Wealth of the United States'; Von Cotta's 'Treatise on Ore-Deposits.'

Later information on this important subject will be found in Mr. J. Arthur Phillips's 'Ore Deposits,' published, I regret, since these pages were written.

[2] The reader should consult the papers of J. Carne, R. Were Fox, and others, in the early volumes of the Roy. Geol. Soc. Cornwall; W. J. Henwood in vols. v. and viii.; the works of Sir H. De-la-Beche, C. Thomas, H. C. Salmon, and the more recent papers of Dr. C. Le Neve Foster and J. H. Collins. Mr. Henwood's papers are a mine of information.

bearing in a given direction, which, when planned on a map, gives their average strike in rectilinear lines. But in reality they follow a waved line, turning off at places and again resuming their former course. They also split and throw off branches, especially when they meet with *cross courses*.

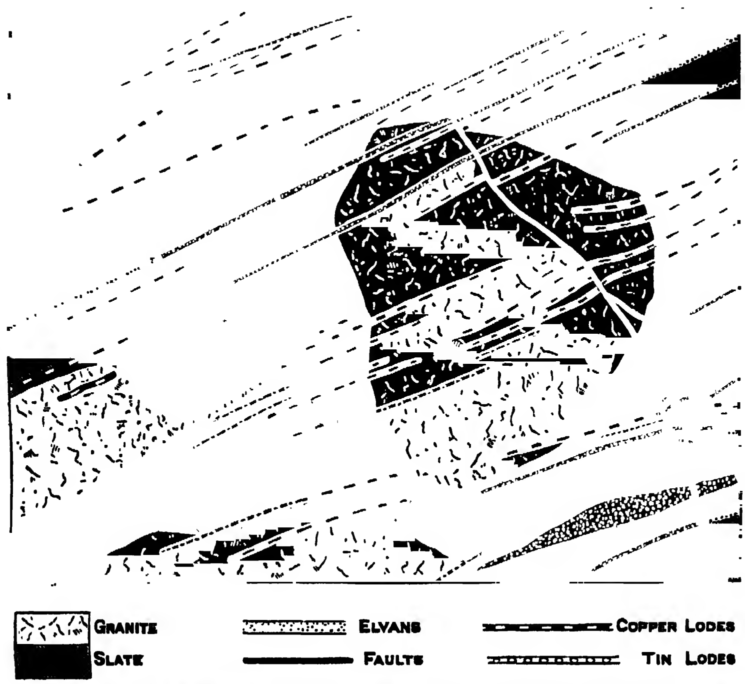

FIG. 167. *Plan of the Redruth Mining District, Cornwall.* (From the Geol. Survey Map.) 1 inch = 1 mile.

This variation has led to considerable difference of opinion with respect to the age and classification of mineral veins, as their age bears a definite relation to their direction. So competent an observer as Mr. J. Carne considered that eight classes of veins could be distinguished; while M. Moissonet, on more theoretical grounds, would extend the number of successive systems of fracture to eleven. On the other hand, Mr. Henwood, Sir H. De-la-Beche, Mr. W. W. Smyth, and others have, owing to the fact that the lodes are subject to changes of direction and variations in their courses of as much as 10° to 20°, concluded they are all reducible to four or five periods of disturbance. The order of succession and the mean general direction of these several systems are as under—

1st. Champion lodes	W. by S. and E. by N.
2nd. Caunter lodes	W.N.W. and E.S.E.
3rd. Cross and flucan veins	N.W. and S E.
4th. Slides with faults	Nearly parallel with No. 2.

Closely connected with the fissuring of the rocks and with the mineral veins, although coming properly under the head of dykes, and needing but a short notice here, are—

Elvans. These are fissures filled with injected rock which traverse alike the granites and the slates. The rock consists of a felsitic base, with crystals of felspar, rarely with mica, and with minute grains or crystals of quartz. This form of quartz-porphyry is termed *Elvanite*. As accessory minerals, the rocks contain schorl (which often lines the numerous joints) and mica, with tin- and copper-oxides in small disseminated granules. In a few instances the tin is in quantities sufficient to be worked.

Elvans vary ordinarily in width from a few feet to 50 or 60 feet [1]. They hold a general course in near coincidence with the E. and W. lodes, or more exactly W.S.W. and E.N.E., and can often be traced for distances of several miles, in one instance as many as twelve miles. Their dip is generally less than that of the *lodes*, averaging about 40° to 60° with the horizon.

The Lodes. The *Champion* and *Caunter lodes* sometimes cross one another, and are commonly supposed to be of different ages; they were, however, considered by Mr. Henwood and Sir H. De-la-Beche to belong to the one common system of E. and W. veins. They both yield the same ores (tin and copper), and are alike in general characters.

The *cross-courses* or *-veins* are fewer in number, and only occasionally metalliferous, the principal ores being galena and iron-pyrites. The following description will apply generally to these three classes of lodes.

Width, Dip, and Length of the Veins. The walls of a fissure are seldom parallel for any considerable distance, and the 'lodes' vary very much in size and importance. Sometimes they are mere chinks; at others they are not less than 30 to 40 feet wide. Mr. Henwood determined from a large number of observations that in—

Granite, their mean width was	3·18 feet.
Slate	3·75 „

While their average width,—

at above 100 fathoms was	3·97 feet.
at below „ „	3·36 „

The 'cross veins' vary in width from 6 to 18 feet, and are wider in granite than in slate in the proportion of 5·0 feet to 3·62 feet.

The veins are occasionally vertical. In an open working in one part of the Dolcoath mine, the enclosing granite walls, after the contents of the vein had been in part removed, formed, in 1858, nearly sheer precipices 60 feet in height, and 20 to 26 feet apart. But more generally the veins

[1] Mr. Hawkins mentions one with a width of 360 feet.

dip at various angles 45° to 90° from the vertical, the inclination of the principal E. and W. lodes averaging about 70°, and that of N. and S. courses about 80°, with the horizon. The plane, however, is rarely uniform, the dip being greater in some parts of the incline than in others, and presenting either a series of curves, or of steps more or less steep (see Sect. of Dolcoath mine, Fig. 171).

As a rule, both the main and the cross-courses dip much more frequently *towards* than *from* the granite; and the veins, which have a nearly meridional direction, are on the whole more highly inclined than those which range transversely to them[1]. According to Henwood, this rule applies also to the mines in the United States.

None of the tin and copper lodes have been traced for more than two or three miles in length, though groups of them extend at intervals through Cornwall and Devon for a distance of 100 miles. It is not, however, probable that the 'lodes' give the length of the fissures, for the metalliferous deposits in the veins being of local occurrence, and the veins ceasing to be worked when they cease to be productive, the fissures may nevertheless be prolonged beyond these unproductive portions, and in connection with lodes at distant places. Some of the 'cross courses' are known to range across the county.

The veins extend with little alteration to the greatest depths (2184 feet) the mines have reached. As before mentioned, Mr. Henwood found a slight decrease in width with the depth; but this may be more apparent than real.

Some of the veins are confined to the slates, and some to the granite; others, on the contrary, maintain their course through both rocks, as well as through the intrusive porphyritic and volcanic rocks.

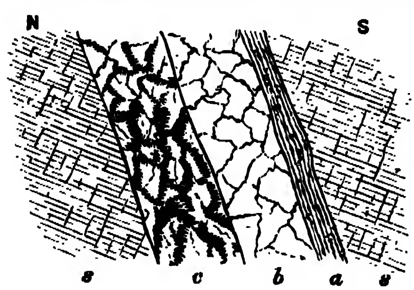

FIG. 168. *Section of the Van Mine Lead Vein, Montgomeryshire.* (C. le Neve Foster.) *a.* Seam of clay. *b.* Bastard lode. *c.* Regular lode. *s.* Slate rocks (see also Fig. 176, p. 321).

The Contents of Mineral Veins. These consist of two parts: 1. the local débris derived from the enclosing walls, and 2. the foreign introduced substances (Fig. 168). The first partake necessarily of the nature of the contiguous rocks. In Cornwall it is sometimes a mass of granitic débris, at other times of angular fragments of slate. Sometimes the débris is small, and forms, with the cementing mineral matter, a breccia; at places the portions detached from the enclosing walls of the fissure are great masses of rock many fathoms in height and length. In some veins

[1] Henwood's 'Address to the Geol. Soc. Cornwall,' 1871, p. 17.

there is no order in the arrangement of the materials; in others they follow a more definite plan.

Sometimes the débris is reduced to a mere clay, which binds together the rubble, and at times constitutes by itself the body of the vein, which is then known in Cornwall as a 'Flucan vein.'

Sometimes, on the contrary, there is an absence of rock débris, and the fissure is entirely filled with minerals more or less foreign to the rocks which the vein traverses (Fig. 169). The most common of these minerals is quartz, which is white and crystalline, and often drusy, and any cavities and fissures are commonly lined with quartz crystals. Secondly, calcite, both massive and crystallised, is a frequent constituent of the mineral veins. Next in order follows fluor-spar, massive and in cubical crystals, and heavyspar (sulphate of barytes). Other minerals are of occasional occurrence.

The mixed veins are however the more frequent, and in them the minerals, though they are generally confusedly mingled with the wall-débris, as in Fig. 168, sometimes form separate distinct mineral masses.

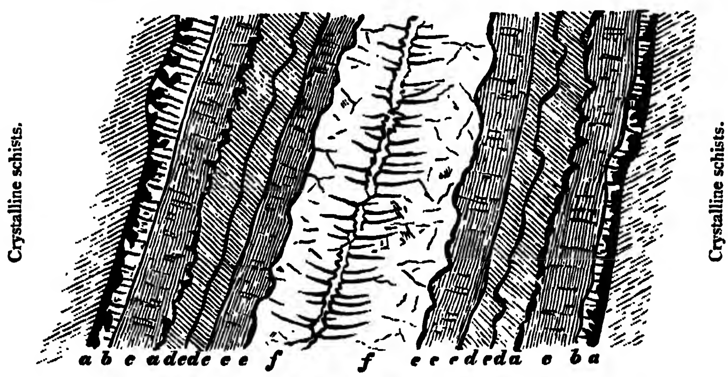

FIG. 169. *Section of the Prinzen Lode, Freiberg.* (Von Cotta.)
a. Blende. *b*. Quartz. *c*. Fluor-spar. *d*. Heavy spar. *e*. Iron-pyrites. *f*. Calcite.

Interspersed amongst these unproductive materials are the metallic ores, the distribution of which is extremely local and irregular. They fill cavities and cracks, sometimes amongst the rock-rubble, at others amongst the introduced minerals. At places they swell out into masses many feet in width and many fathoms in length; at others they diminish to mere threads. The metalliferous veins are generally restricted to disturbed areas, and are commonly associated with the presence of crystalline and intrusive rocks. Mr. W. W. Smyth states that in Cornwall and Devon, no productive tin- or copper-mine appears ever to have been opened at a greater distance than from two to three miles from the edge of the granite, though valuable lodes of iron-ore, antimony, manganese, and lead (often highly argentiferous), have been explored and worked to much greater distances, and to depths of 200 and 300 fathoms. Between the granitic

centres of Wendron and St. Agnes, in a district nine miles in width, there may be counted as many as fifty to sixty parallel tin- and copper-lodes, intersected by cross-courses of great extension and regularity [1]. The great tin- and copper-lodes, as a rule, are the E. and W. lodes, while the cross-courses are mainly lead-lodes.

Generally, the contents of lodes are not symmetrically arranged. There are, however, cases (*combed* veins) where the deposited minerals are in successive and regular layers (Fig. 169).

Mr. Henwood called attention to the important fact that, in all lodes, whatever may be the nature of their ores, the parts most highly inclined are always the most productive. Every lode also throws off into the adjoining rock *branches* and *strings* (Fig. 175). Lodes and branches are generally rich at their junctions. Beyond, on the other hand, the separation and splitting of veins tend to poverty.

Extraneous bodies in Veins. From time to time pebbles and fossils not belonging to the enclosing rocks are met with in the Cornish veins. Some years ago at Relistian in the parish of Gwinear, a mass of pebbles of slate and quartz, 12 feet in length and height (with scattered pebbles beyond), was found at the junction of a flucan (clay) vein and of a tin-lode traversing slate, at a depth of 450 feet from the surface. Many of the pebbles were encrusted with tin-ore [2].

At Duffield, in the same parish, there occurred, in a copper-lode traversing slate, between the lode and the wall, a layer of slaty matter containing rounded stones of slate, quartz, and elvan, extending from the depth of 526 feet to 586 feet. At Trevaskus in the same parish, a lode of tin- and copper-pyrites, also in slate, contained, between the depths of 200 and 300 feet, rounded masses of slate, quartz, and copper-pyrites. At Herland, in the same parish, irregular and rounded stones, of slate, granite, and elvan, were discovered in a lode of copper-pyrites traversing slate rock intersected by granite veins. A lode of tin and copper in the granite of St. Just contained, at a depth of 384 feet, 'globular quartz stones [3].' Other observations made in these districts render it uncertain whether these are really introduced pebbles from the surface, or whether they may not, in some cases, be derived, like the angular rubble, from the enclosing rocks.

At Altenberg in Saxony, pebbles of quartz similar to those in the beds of streams were found in a lode traversing gneiss; and some veins near Chalanches in Dauphiné are said to have been entirely filled with pebbles; but no further particulars are given [4].

[1] British Association Lecture, Plymouth Meeting, 1877.

[2] Carne, 'Phil. Trans.' for 1807, p. 293, and 'Trans. Royal Geol. Soc. Cornwall,' vol. iii. p. 238.

[3] Henwood, 'Trans. Roy. Geol. Soc. Cornwall,' vol. v. p. 183.

[4] Daubuisson, 'Traité de Géognosie,' vol. ii. p. 642.

Together with the débris of the enclosing walls, fossils of these rocks are not unfrequently recorded from the veinstones of lodes. The fluorspar of the Derbyshire lodes occasionally contains well-preserved specimens of encrinital plates and columns from the Carboniferous Limestone which the lodes traverse.

But the most remarkable instance is that recorded by the late Mr. C. Moore, at Old Charterhouse Lead-mine, in the Mendip Hills, where, on the high summit of the Carboniferous Limestone, and at a depth of 270 feet from the surface, he found a deposit of bluish clay 10 feet thick intercalated in the lode. By careful washing of this clay, he obtained above thirty species of Lias fossils, not including the Foraminifera, and above twenty species of Carboniferous fossils [1]. Above the clay débris was a marl passing upwards into a compact conglomerate with water-worn pebbles, succeeded by sandy beds with some worn stems of Carboniferous encrinites and small pebbles of hematite, and then by a calcspar veinstone with the largest deposit of lead-ore (galena). Detached crystals of galena occurred in the Liassic débris. Mr. Moore considered these and other Mendip fissures to be of pre-Jurassic age, and to have remained open under the sea during the Liassic period. At present there is no Lias within two miles of the mine, and there it is at a lower level. It is possible that some of the débris may have been washed in at later periods.

Mr. Moore also examined the fissure-débris from a mine in Flintshire, and from three mines in Yorkshire and Cumberland—all in the Carboniferous Limestone, and obtained from them 112 species of organic remains, including, according to him, some of the same land and freshwater shells found in the Charterhouse mine, and eight new species of Foraminifera. In these mines, moreover, all the fossils were, he considered, of the same age as those of the local rock.

Cavities in Veins. Sometimes the 'gangue' is compact and solid; at other times it is full of small cavities and holes. Some few are larger, and form spaces several fathoms in length and depth. At Dolcoath Mine, in the parish of Cambourne, a number of such cavities were met with in a lode traversing granite and slate. They were about 20 feet high, 4 to 9 feet wide, opening into each other, and extending for a length of 60 feet. In a lode, in slate, at the Consolidated Mines, Gwennap, a great cavity (the local name is a 'vugh'), 240 feet long and 6 to 12 feet high, was discovered between the 660 and 720 feet levels. It was lined in places with large crystals of quartz.

---

[1] 'Quart. Journ. Geol. Soc.,' vol. xxiii. p. 491, and Reports Brit. Assoc. for 1869, p. 360. Mr. Moore also found specimens, which he believed to be of land and fresh-water species referrable to *Helix*, *Valvata*, *Vertigo*, *Planorbis*, and *Hydrobia*, which he at first thought to be of Liassic, but afterwards came to the conclusion that they were of Carboniferous age. This remarkable fact, however, requires confirmation, for although *Pupa* has been found in Carboniferous rocks, it was under very different circumstances.

Slickensides. Occasionally it is difficult to note the line of separation between the lode and the enclosing rock ('country'). At other times it is not only easily seen, but the line is sharply marked by a *slickenside* surface. This surface is not unfrequently covered with a coating or glaze of iron- and copper-pyrites or of galena, showing rectilinear striation, generally corresponding with the dip of the vein, but at times running at various angles, indicative of movements in different directions. (See Fig. 121, p. 254.) These movements seem to have been in many cases often repeated. The veins would appear also in some places to have been enlarged and opened out after the deposition of a portion of their contents; and slickensides sometimes run irregularly through the whole substance of the lode.

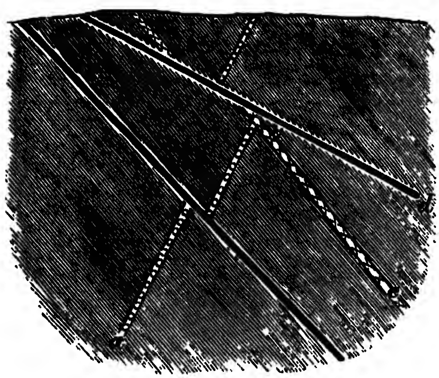

FIG. 170. *Section of 'veins' intersected by 'faults,' Huel Peever Mine, Cornwall.* (Carne.) *a.* Tin lode. *c.* Copper lode *d.* Slides (faults).

Slides. These are more restricted in their range, and are of later and possibly of several dates. They have a general east and west course, and intersect indiscriminately the elvans, lodes, and cross-courses. Their width rarely exceeds 2 to 12 inches, and they contain no metallic ores. They are, in fact, ordinary faults or slips (Fig. 170). According to Henwood they are few in number, and their vertical throw is usually small, the greatest mentioned by him not exceeding 114 feet. They are not in general inclined to the horizon at angles greater than 40° to 45°, some being nearly horizontal, and none have been recorded in granite.

Age of the Cornish Lodes. It is supposed that the great central masses of granite in Cornwall and Devon were protruded through the Palæozoic strata at a period subsequent to the formation of the Carboniferous rocks. Of the general correctness of this opinion there can be no doubt. Nevertheless, there seems to be evidence, that some masses of granite did exist in or near that area before the deposition of the Silurian and Devonian strata, and that they were not far distant; for from time to time there have been found in some of the deep workings in the slates or killas of Silurian and Devonian age, blocks of granite of various sizes, which seem in no way connected with intruded or metamorphic masses; nor, although in the proximity of lodes, do they appear to belong to the rolled blocks and pebbles found in the lodes.

Mr. Henwood[1], referring to the blocks of granite and quartz found in the slate at Herland, at a depth of 660 feet, states that they varied in

[1] 'Trans. Roy. Geol. Soc. Cornwall,' vol. v. pp. 36, 72, and 157.

size from a hazel-nut to blocks 2 to 3 feet in diameter; and that they were ***entirely enveloped by the slate, and were not in contact with the lodes, or with any of the small strings of quartz traversing the granite;*** while the nearest indication of granite on the surface is 3 to 4 miles distant from Herland. Similar masses were found at Wheal Buller, at a depth of 294 feet. Mr. Salmon[1] describes the occurrence of numerous pebbles and boulders of elvanite, tourmaline-rock, and granite (two of which latter he estimates at 6 feet in width and depth and 4 to 4½ feet in length), at the sides of a lode in the slate in the parish of Gwinear, at a depth of 444 feet. Two of the smaller boulders were more angular than the others. He considers them (but without, it seems to me, sufficient reason) to be in some way connected with the constituents of the lode. Another instance is mentioned by Mr. James[2], where in a mine worked in the slate in the parish of St. Hilary, and 1½ mile distant from any granite outcrop, a block of granite much larger than a 'bullock' was found embedded in the killas at the depth of about 360 feet. These facts would seem to point to pre-Silurian granitic lands.

It is clear, however, from the many well-known instances of the intrusion of veins of granite through the surrounding killas (see Fig. 218, p. 444), that the great protrusion of the granite was subsequent to the deposition of the Palæozoic strata. To the granitic bosses succeed the elvans, whose relative age is clear, for they traverse both the granite centres and the surrounding slates. At the same time there is at least one, if not two instances, of an elvan dyke intersecting a mineral vein; showing either that one system of veins is older than the elvans, or that there is more than one system of elvans.

FIG. 171. *Section of Dolcoath Mine.* ('Tr. Roy. Geol. Soc. Cornwall' for 1883.)
s. Killas (slate rocks.) *g.* Granite. *e.* Elvans. *x.* Copper and tin veins.

The great body of the E. and W. tin- and copper-lodes, however, are of later date than the elvans; and, although they generally run in parallel lines, they cross (and sometimes dislocate) the latter in the manner shown in the above section of the great Dolcoath Mine.

These 'E. and W. veins' differ at places considerably in their orienta-

[1] 'Quart. Journ. Geol. Soc.,' vol. xvii. p. 517.
[2] 'Trans. Roy. Geol. Soc. Cornwall,' vol. ix. p. 101.

tion, varying as much as from 22° S. of W. to 35° N. of W. While some geologists consider all of them to be of the same age, and the variation in their course merely local, others consider they are of two or more ages, as they not only strike, but also underlie differently, and one set is sometimes 'heaved' by the other [1], as in the accompanying section of Sealhole Mine.

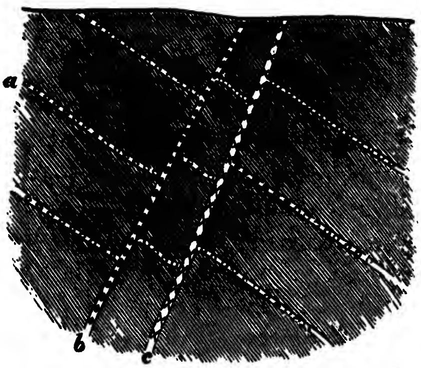

FIG. 172. *Section of Sealhole Mine*, Cornwall. (Carne.) *a*. Tin Lodes. *b*. Newer tin lodes. *c*. Copper lode.

The many and considerable differences in the direction of the E. and W. lodes have even led M. Moissonet to divide this set into six systems, varying in age from the system of Finisterre (or Cambrian) to that of the Pays Bas (or pre-Triassic). But, looking at all the phenomena, and to the circumstance that the protrusion of the great mass of the granite is evidently post-Carboniferous, it is difficult to admit M. Moissonet's conclusions; at the same time his work is one of interest, on account of the general discussion of the question, and the elaborate array of facts [2].

The 'cross-courses' which intersect the E. and W. veins at angles of from 60° to 90° are of later date than the veins which they frequently displace or *heave*. Owing to the uniform character of the enclosing rocks, it is not easy to determine the extent of vertical throw, or of horizontal displacement, which latter may even, in some cases, have been caused by the vertical displacement of the inclined veins independently of any horizontal motion. The joint result is known in Cornwall as the 'heave,' that being the measure of total displacement both vertically and laterally—or, as they say, to the right or to the left. Of 272 lodes traversed by cross-courses, Mr. Henwood found that 20 per cent. suffered no vertical displacement, while the greatest displacement amounted only to 17½ feet, the average being 15¾ feet [3]. There are cases, however, where the horizontal heave amounts to 400 or 500 feet or more; in one, but more uncertain, instance, it was estimated at 1200 feet [4].

That there has been in some cases a considerable lateral as well as vertical movement is the general opinion of Cornish geologists. Instances are mentioned where an intersected lode is not heaved at a depth of 150 feet, while at a depth of 630 there is a heave of 72 feet; and others where a lode is heaved to the right in the upper part of its course, and to

[1] Carne, 'Trans Roy. Geol. Soc., Cornwall,' vol. ii. p. 87.
[2] 'Observations on the rich parts of the lodes of Cornwall,' translated by Mr. J. H. Collins, 1877.
[3] 'Address of 1871,' p. 31.
[4] 'Trans. Roy. Geol. Soc., Cornwall,' vol. ii. p. 118.

the left in its lower part, and *vice versâ.* Much of course depends on the dip of the vein and the angles of intersection.

The 'cross-courses' are referred by M. Moissonet to five systems of disturbance, the oldest being that of 'La Vendée' (or pre-Cambrian), and the latest that of the 'Ballons' (or pre-Carboniferous); but the displacements effected by the cross-courses are, it would seem, decisive of their all being of later date than the lodes.

Mineral Veins in Limestones. These are generally true faults, in which metallic ores are present. We may take the lead-mines of Cumberland and Derbyshire as the type of these veins. The Carboniferous Limestone of the Cumberland district is traversed by numerous faults, which displace the strata, sometimes only to the extent of a few inches, at other times of many hundred feet. There are two main systems of faults, one varying in direction between 10° and 20° E. and W., and the other running in a direction nearly N. and S. A few smaller veins strike at intermediate angles. The first-mentioned system is the richest in ores,—

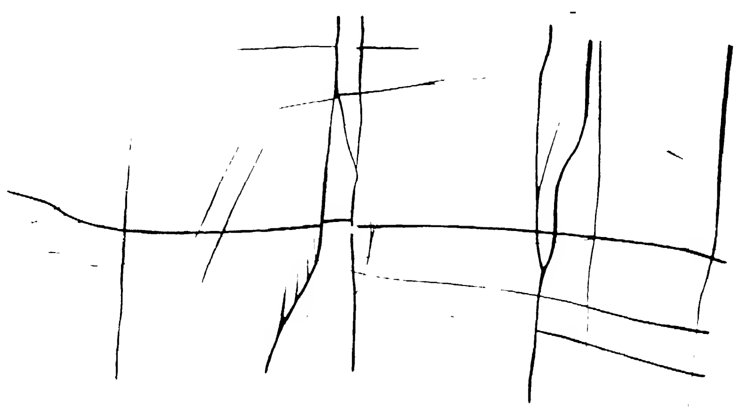

FIG. 173. *Ground-plan of the Lodes in part of Alston Moor mining district.* (Wallace.) 1 inch = 15 chains. The numbers give the difference of level in feet on the upthrow side of the fault-veins.

chiefly galena; the others contain lead with some copper. The above plan gives their general strike and throw. Mr. Wallace states that in Alston Moor, as a general law, the joints of the rocks are more numerous as well as more open near the surface; but he considers any coincidence of direction to be merely accidental.

Some of the E. and W. veins or faults have a throw of from 60 to 80 feet; while one of the cross (N. and S.) veins is accompanied by a displacement of the strata to the extent of 260 feet. These latter are generally considered to be of later date than the E. and W. veins; but Mr. Wallace seems of opinion that they are either anterior to or contemporaneous with

them. He considers, however, with good reason that both sets of veins are of a date subsequent to the Carboniferous period, and before the Permian period.

In this district the throws, when small, give rise to but small spaces between the dislocated strata; and there is little mineral ore. With an increase in the throw, the space between the walls of the limestone and sandstone beds, together with the size of the lode, increase; while the shales and softer strata, closing in, are unproductive. Annexed is the section of a cross-vein which contained a rich deposit of ore between the walls of the limestone, the vertical displacement here being about 26 feet.

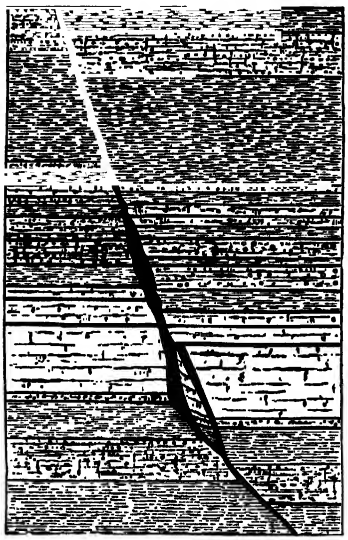

FIG. 174. *Section of a Lead Vein, Alston Moor.* (Wallace.)

In Fig. 175, the throw is about 60 feet, and the upper part of the fault is split up into numerous branches.

In some of these mines the veinstone consists chiefly of carbonate of lime, fluorspar, and iron-oxide; in others, quartz predominates. A narrow strip of ore often lies against the limestone-walls, the rest of the space being filled with calcite and fluorspar containing small masses or nests of galena. Sometimes the centre is cavernous, with crystals of fluorspar lining the sides of the open space. Though generally narrow, one great vein, still supposed by Mr. Wallace to be a fissure-vein, forms an exception, attaining in one place a width of 300 feet. He considers its formation to be analogous to that of the great adjoining Whin-Dyke, with which it runs parallel.

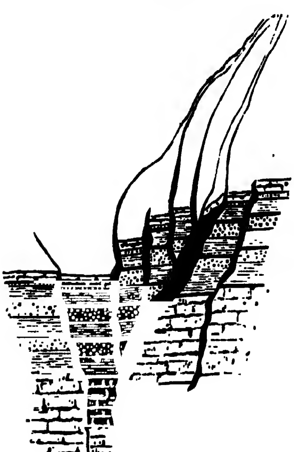

FIG. 175. *Section of a split* 'Fault' *Vein, Alston Moor.* (Wallace.)

The prevailing ore is galena, which, as in the Derbyshire mines, most abounds between the walls of limestone in the upper part of the series.

In the strata below the Great Limestone the veins contain some copper-pyrites as well as galena.

In Cumberland the open joints of the rocks are usually filled with clay or rubble; in Derbyshire they not unfrequently contain galena, which is connected with the leaders or veins that traverse the strata in fissures independently of the joints.

Wales. The veins in the Silurian rocks of Cardiganshire [1] are also mainly fault-veins; though owing to the preponderance of slates and the absence of distinct strata, it is difficult to determine the throw. The veins are filled largely with slate in angular fragments, of all sizes,—some of them ('horses') many fathoms in length. These are cemented in part by crystalline and drusy quartz, and in part by calcite with spots of copper, lead, and zinc ores. One vein contains carbonate of barytes and occasionally carbonate of lead. The lead-ore is galena, so rich in sulphide of silver that it yields sometimes seventy-five ounces of silver to the ton. There is no apparent order in the deposition of the metals and minerals. The walls of the vein are in places a few feet and in others several feet apart. The lodes strike E.N.E. and W.S.W., and are intersected by small cross-slides or faults filled with clay.

The Van Mine in Montgomeryshire, the most productive lead-mine in Britain, is a fissure-vein [2]. Its direction is about E. 26° N., and its dip about 74° S. It has been followed for a length of 9 miles, and to a depth of 720 feet. The vein is usually several fathoms wide, and the ore-bearing part attains in places a width of 48 feet. The in-filling consists of—1st. *a*, a mass of clay and soft broken slate ('flucan'), from 12 to 24 feet thick, which comes next to the 'hanging-wall [3]' of the fissure; 2nd. *b*, a body of soft slate rubble traversed by little veins and strings of galena, 20 to 30 feet wide, and divided from the true lode by a wall or thin seam of yellowish limestone (?); 3rd. *c*, the lode, which consists of veins of galena, varying in size from mere strings to *leaders* or *branches* 1 to 2 feet wide, in a débris of slate, mixed with quartz and blende, together with a little iron pyrites, copper-pyrites, and calcite. The lode is in places a true breccia. Further details of this fine vein will be found at p. 312, Fig. 168.

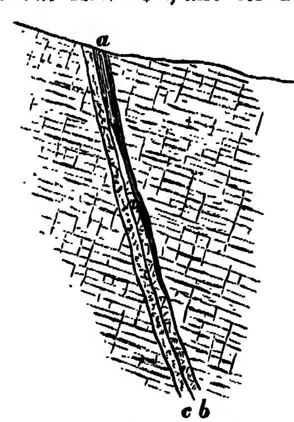

FIG. 176. *Section of the Van Mine.* (C. Le Neve Foster.)

Quartz Veins. Another form of mineral-vein,—differing only in

[1] W. W. Smyth, 'Mem. Geol. Survey,' vol. ii. p. 655.

[2] Dr. C. Le Neve Foster, 'Trans. Roy. Geol. Soc. Cornwall,' vol. x. p. 33.

[3] Meaning the upper side in an inclined vein.

the circumstance of uniformity of *gangue*,—is that in which the fissure is filled altogether or in greater part with amorphous quartz, through which is disseminated certain quantities of native metals with small proportions of ordinary ores. They are rare in this country, although not altogether absent. Auriferous quartz-veins exist in Wales and in Ireland. In Merionethshire [1] veins of white saccharoid quartz, with chlorite and calcite, traverse the Cambrian rocks and range W.N.W. and E.S.E. They contain, besides galena and blende, small flakes and grains of gold and native silver. In Caermarthenshire veins of massive quartz, with some cubical iron-pyrites and specks of galena, associated with a few particles of gold, were worked by the Romans [2]. Attempts have been made of late years to work the veins near Dolgelly, but they have hitherto been attended with only partial success. Auriferous veins exist in North Devon, and small quantities of gold have been found in the quartz in the veins (more particularly in the 'gossan' or uppermost decomposed portion of the vein) of Cornwall [3].

In Ireland traces of native gold and silver have been met with in veins traversing the Crystalline and Palæozoic rocks of Wicklow, although there, as in Britain, the metal has been chiefly obtained from detrital river sand and gravel. One nugget was found weighing twenty-two ounces [4].

Although the quantity of gold now obtained in Great Britain and Ireland is extremely small, it is evident that in the river-gravels it was formerly found in larger quantity, especially in Ireland. A considerable quantity also is said to have been formerly obtained from this source in the neighbourhood of the Leadhills in Scotland; and more recently gold has been found in detrital beds in Sutherland, but nowhere in these islands has this source of late afforded productive workings.

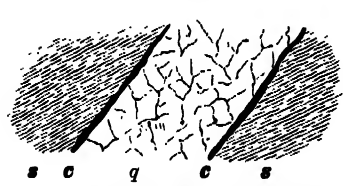

FIG. 177. *Auriferous Quartz Vein, Australia.* *q*. Milk-white quartz, fissured into fragments, 30 feet thick, with gold in grains, ramifying filaments, and lining cavities and fissures. *c*. Seams of clay with iron-oxide and traces of gold. *s*. Silurian schists.

The auriferous veins generally are in rocks of Palæozoic age, and this was at one time supposed to hold good universally; but, as we shall show presently, there are many cases in which it does not hold.

The annexed example of an Australian quartz-vein may serve as a general illustration of the character of such veins in all parts of the world. They vary from a few inches to several yards in width.

Other Forms of Lodes. The distribution of the metallic ores in some of the sedimentary, and more especially in the igneous and metamorphic rocks, takes special forms, dependent upon certain local

[1] Ramsay, 'Quart. Journ. Geol. Soc.,' vol. x. p. 242.
[2] W. W. Smyth, 'Memoirs Geol. Survey,' vol. i. p. 480.
[3] Pattison, 'Quart. Journ. Geol. Soc.,' vol. x. p. 247.
[4] Weaver, 'Trans. Geol. Soc.,' vol. v. p. 209.

conditions, some of which are not yet well understood. Of these abnormal deposits, the most important, in a geological point of view, are *floors*, *flats*, *stockwerks*, and *fahlbands*.

The first two relate to ores occupying lines of joint and bedding, but which are in all cases connected primarily with adjacent veins. In this respect, the *flats* and the *skrins* of the midland and northern counties, and the *floors* of Cornwall, represent somewhat analogous conditions. In Cumberland horizontal masses (*flats*) of galena, many feet in width, and from an inch to several feet in height, fill spaces between the bedding of the limestone and of the strata with which it alternates (Fig. 178). They are likewise common in the Carboniferous Limestone of Derbyshire, where the metal spreads into the joints of the rocks (*skrins*), or accumulates into irregular cavities (*pipes*).

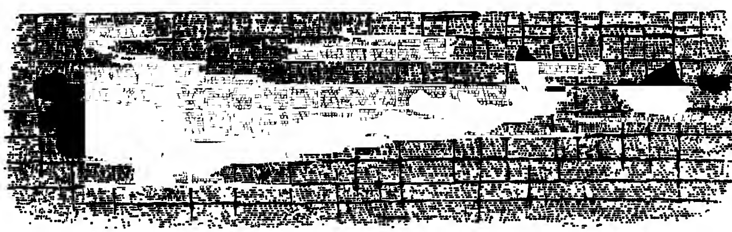

FIG. 178. *Groundplan of part of a 'Flat' Lead Lode, Alston Moor.* (Wallace.) *a*. Limestone. *b*. Lead ore (galena). This 'flat' occupies an area of eight acres. Part of it consists of open caverns (one of which was 20 cubic fathoms in size) lined with calcspar, galena, and blende.

One of the most remarkable of these *flats* occurred in Flintshire, on the line of junction between the Carboniferous Limestone and the Millstone-grit. It was from 1¼ to 8 feet thick—the metalliferous portion averaging 14 inches thick—and followed the dip of the strata. It was found to extend over a horizontal distance of half a mile[1]. Strings of the ore (galena) were traced from this main mass 30 feet downward in the limestone and 18 feet upwards in a calcareous sandstone, proving the introduction of the mineral to be subsequent in age to both limestone and grit.

In Cornwall the 'killas' is sometimes traversed by little veins of quartz, accompanied by schorl, and occasionally these enlarge and contain tin-ore. In the proximity of these veins lenticular masses of tin-ore occur, interposed between the planes of bedding in the killas. In a similar way the joints of the granite (and probably of the killas also) are sometimes filled with ore. These tabular masses are termed 'floors[2].' The quantity of metal is, however, generally so small that the veinstone and enclosing rock have both to be worked together.

Around St. Austell, the granite is frequently intersected with small joints filled with quartz, schorl, and oxide of tin. They often form a

[1] De la Beche, 'Geological Observer,' p. 785.

[2] Hawkins, 'Trans. Roy. Geol. Soc. Cornwall,' vol. iii. p. 29; C. Le Neve Foster, 'Rept. Min. Assoc. of Cornwall and Devon' for 1875.

network of parallel, but irregular veins, and are especially conspicuous in the great open mine of Carclaze. In some instances the tin ore has clustered in a cloud of fine particles round the tin-vein or -seam (Fig. 179).

This form of structure, known on the Continent under the name of *Stockwerk*, gives rise in some parts of Germany to extensive works. *Fahlbands* is another special condition of ore-deposit peculiar to some parts of Europe, which we shall describe presently in noticing the mineral-veins of particular areas.

FIG. 179. *Section of a Tin Seam in East Wheal Lovell Mine.* (C. Le Neve Foster.)

France. The argentiferous lead-lodes near Morlaix in Brittany are in strata of Lower-Silurian age, and range N.N.W. and S.S.E. The veins in the gneissic and granitic rocks of Central France contain, besides some lead, manganese, antimony, and copper-pyrites, and range mostly N. and S. This also is the direction of the many great argentiferous lead-veins of the Vosges, one of which has a width of 65 feet, while others, which run nearly E. and W., contain ores of copper, lead, cobalt, and arsenic [1].

In the Pyrenees there are few mineral-veins, and they consist chiefly of iron-oxides and carbonates, traversing strata of Lower-Jurassic age, with some probably of Cretaceous age. There are also some mixed copper- and lead-lodes; and in other places there are traces of gold. On the Spanish side of the Eastern Pyrenees, Palæozoic rocks are traversed by a few auriferous quartz-veins, ranging N.E. and S.W.; and these are intersected by more recent lead-lodes.

The Alps are, in general, poor in mineral-lodes. The central crystalline axis contains some argentiferous and a few auriferous quartz-veins; and in the Jurassic limestones of the Alps of Dauphiné are veins, striking N. and S., of antimony, copper, cobalt, etc., with some silver. In the Triassic rocks of the Eastern Alps there are a few lodes of copper and lead, with a general E. and W. strike, though there are others running N. and S. The veins of the Central Alps abound, however, in beautiful specimens of various non-metallic minerals.

Germany. The valuable lodes of silver-ores in the Devonian schists of the Andreasberg district of the Western Hartz strike E.S.E. and W.N.W., and are crossed by others running S.S.E. and N.N.W. These lodes have been worked and found productive to the depth of 2600 feet. The Clausthal district is traversed by a number of broad fissures in strata chiefly of Carboniferous age, and ranging on the whole E. and W., or parallel to the chief axis of the Hartz. The contents of the veins consist, in large part, of fragments of the wall-rock much altered, mixed with argentiferous galena, blende, copper- and iron-pyrites. A feature in these

[1] Burat, 'Minéraux utiles,' p. 229.

lodes is that the fragments of clay-slate often form nuclei surrounded either by quartz with galena and calc-spar, or, first, by a layer of spathic iron, and then by quartz and other minerals,—sections of them showing a ringed or concentric structure[1]. Veins of manganese-ores occur in the porphyritic rocks around Ilfeld; while antimony, lead, and silver are found in the Silurian strata of the Eastern Hartz.

The crystalline schists and clay-slates of the Erzgebirge contain a great variety of mineral-veins; but the district of especial interest is the celebrated one of Freiberg. The lodes of that district contain lead, silver, copper, arsenic, zinc, etc. More than 900 of them have been counted, but it is possible that some may be on the prolongation of the same fissure. They form three groups, each group running in separate directions. One group, consisting chiefly of lead- and copper-ores, has a strike of from N.E. to S.W., with a nearly vertical dip. Another group of lead-veins has a direction N. and S., with a less steep dip, and intersects the first group often at acute angles, the junctions being distinguished by a special richness in ores. A third group of lead-veins (galena), with heavyspar, blende, and a great variety of crystallised minerals, strike N.W. to S.E., and intersects and *throws* both the other groups. There are also a few lodes with intermediate strikes.

This remarkable network of fissures is crowded into a tract about ten miles in length and five miles in breadth. The veins are mostly of small width, 1 to 7 feet; and none of them have been traced for more than from 1 to 4 miles in length. To the N.W. of this district, but distinct from it, there is another group of veins, traversing gneissic and schistose rocks, and ranging from N.E. to S.W., and nearly parallel to the first group. These veins consist of quartz with silver-ores and a number of non-metallic minerals. Elsewhere in the granitic and schistose tracts of the Erzgebirge district tin-lodes with a general strike E. and W., copper-lodes striking N.E. and S.W., and iron-lodes N.W. and S.E., are worked.

In the district of the Thuringian Forest the Silurian strata contain veins of limonite, passing down into hematite; in the quartz-porphyries are veins of manganese and iron-ores; and, in the Carboniferous rocks, argentiferous ores. But the most metalliferous rock in that area is the Zechstein, which is rich in iron-ores of various descriptions. Of these the most important consists of limonite, resulting apparently from the decomposition of spathic iron by the surface waters. There is some doubt, however, whether these are really lodes or masses of contemporaneous origin[2].

Ores of mercury are found in veins, having a clay matrix, and traversing the Carboniferous rocks of the Palatinate. The metal impreg-

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[1] Cotta's 'Treatise on Ore Deposits,' p. 156.

[2] The copper ores of Mansfeld and other places in the Hartz district are sedimentary shales (Kupfer Schiefer) impregnated with sulphide of copper, and lying at the base of the Zechstein.

nates the sandstones on either side to the distance of several fathoms. The lodes have not been followed to a greater depth than 720 feet, as their richness decreases very perceptibly with the depth.

Carbonate of zinc (smithsonite), limonite, and galena occur in vertical fissures—seemingly lines of joint—in the Muschelkalk of Wiesloch in Baden.

The gold in the old river-gravel of the Rhine valley is supposed by Cotta to have come originally from the crystalline rocks of the Alps; but it is derived immediately from Tertiary sedimentary strata—the Molasse.

Metallic lodes exist in Bohemia, Silesia, Transylvania, Servia, Hungary, Northern Italy, and Spain; but we can only notice a few prominent cases, referring the reader for details to the special works before mentioned.

The gold-mines of Transylvania are situated in a mountainous tract of crystalline schists, succeeded by Mesozoic limestones and Eocene sandstones. The district is traversed by a number of mineral veins, many of them auriferous, and is also, like that of Schemnitz in Hungary, much disturbed by trachytic eruptions of Tertiary age. The veins traverse both the older schists and limestones and the newer Eocene strata. The gold occurs both native and in combination with the rare metal tellurium, together with iron-sulphide. The veins generally run N. and S., or N.W. and S.E., and the gold is so finely disseminated in the ground-mass that it is not visible to the eye. It also penetrates the adjacent rock so that both vein and enclosing rock are worked and taken out together. The mines were known to the Romans, whose fine galleries still surpass the works of their successors, and show that the extraction of gold from rocks in which it was not visible was even then understood [1].

Spain. The mercury-mines of Spain are very important. This metal is of far rarer occurrence than gold, being confined in Europe to a few localities, of which Almaden in Spain and Idria in Austria furnish nearly all the supplies. Although so rare elsewhere in the old world, the abundance of the ore at these places is remarkable. At Almaden the lodes consist of quartz traversed by strings and masses of cinnabar, with occasionally some native mercury. The enclosing strata are of Upper-Silurian age. The average breadth of the ground worked is 21 feet, increasing with the depth—which in 1851 reached 1050 feet—to nearly 40 feet. Some uncertainty has seemed to exist whether the mine consists of veins or whether it is a case of bed-impregnations. Le Play, however, considers the lodes to be true veins. They have a dip near the surface of 60° to 70° with the horizon; but, as they get deeper, the dip becomes nearly vertical. Their strike is E. and W.

North America. Amongst the mineral-veins of North America are the extraordinary lodes of native copper of Keweana Point, Lake Superior. The rocks consist of sandstones and conglomerates of Lower-Silurian and

[1] W. W. Smyth, 'Mem. Geol. Survey,' vol. i. p. 483.

Cambrian age, with contemporaneous trap-rocks. The veins consist of drusy quartz, with calcite and prehnite, mixed in places with fragments of the adjacent rocks. They vary in width from 1 to 10 feet or more, have a nearly vertical dip and a very regular course, and cross the strata nearly at right angles to the strike. The copper occurs in pieces of every size, from almost microscopic particles to masses of from 1 to 200 tons or even more in weight. An interesting point to notice is the occasional occurrence of grains of pure silver, giving the copper a speckled appearance, and of small radiated nodules of prehnite enclosed in the pure copper. In places the copper has also been found laminated—a structure referred by Professor Le Conte[1] to pressure and sliding, such as have caused slickenside surfaces in other veins.

In 1854 Professor Whitney wrote, 'there is no proper silver-mine within our territories, although there are several localities where a small amount of this metal is obtained in connection with lead-ores.' In 1867 the Comstock mine alone yielded silver to the value of £3,300,000. This wonderfully rich mine is situated in Nevada, at an altitude of 6000 feet. The strike of the vein, which is a fissure-vein, is nearly N. and S. It varies in width from a few inches to 200 feet, and extends more than four miles in length. The vein has large selvages of clay with broken portions of vein and rock, much worn and rounded, and throws out many branches. The ores are sulphides of silver, lead, iron, etc., with native silver, and some gold. The mine is also remarkable for the high temperature of the water which issues from the lode. At the great depth of 2660 feet, which the mine had reached in 1876, this stood at 157°Fahr.[2]

As in Europe, so in America, gold is very widely distributed; but it has been profitably worked in two regions only—the flanks of the Appalachian range and California. The original site of the metal in California is in veins of quartz traversing granites, greenstones, metamorphic slates, quartzites, sandstones, and conglomerates,—strata which, unlike most other places where the veins are in rocks of Silurian or other Palæozoic age, are, by many of the American geologists, supposed to be in great part of Jurassic and Cretaceous, if not indeed of Tertiary age. The veins are said to conform to the dip and strike of the strata, and to vary in width from a few inches to 20 or 30 feet. The most extensive vein, known as the 'mother-vein,' has been found to follow, with some breaks and interruptions, a zone of Jurassic slates and sandstones for a distance of 80 to 100 miles.

Mexico. The great silver-lodes of Mexico are situated in strata of Carboniferous age. They range approximately N.W. and S.E., and dip at

[1] 'Proc. Amer. Phil. Soc.,' vol. xviii. p. 249.

[2] Blake, 'Report on the Production of the Precious Metals,' p. 2. The hot Steamboat springs are only seven miles distant; J. A. Phillips in 'Quart. Journ. Geol. Soc.,' vol. xxxv. p. 393.

a high angle. While the majority of the lodes vary from a few inches to 6 feet in width, some few are remarkable for their greater size. One lode widens out in places to 200 feet, and has been traced for a length of nearly 10 miles, and to a depth of more than 2000 feet; another has an average width of 25 to 30 feet. The gangue consists chiefly of quartz, with fragments of the enclosing walls. The ores are sulphides of silver, which near the surface have been decomposed and replaced by metallic silver, silver-oxide, -carbonate, -chloride, etc. The veins also generally contain much ferruginous matter. Duport was of opinion that the yield of silver does not continue to be so good at great depths as nearer the surface.

South America is rich in mineral veins; but, owing to difficulties of extraction and transport, the working of them has been almost altogether confined to those of the precious metals and of mercury.

The silver-mines on the high table-lands of Peru and Bolivia are in strata probably of Carboniferous and Jurassic age; and the ores at depths consist of sulphides, arsenides, and antimonides of silver, which, like those of Mexico, have undergone decomposition near the surface. With the increase of depth the deposits have also, it is said, been found to grow sensibly poorer. The strike of the veins is N. and S. One of them has a length of nearly two miles, and a width, in places, of above 400 feet. In Chili, according to Darwin [1], the principal mineral veins generally strike N.N.W. and S.S.E.; they are connected with the presence of intrusive rocks, and seemingly also with the degree of metamorphic action which the associated rocks have undergone.

Henwood states that the copper-lodes in the hornblendic and quartzose rocks of Copiapo have two directions, namely, 25°–30° S. of E. and N. of W.; and 30°–35° W. of N., and E. of S.; and that the silver-lodes in the limestones of Chañarcillo bear 38° E. of N. and W. of S., dipping W. 65°–74°, while the cross-veins coincide in direction with the joints of the limestones [2].

Australia. The gold-veins of South-Eastern Australia are typical. A centre of intrusive granite has burst through schistose rocks of Silurian age, which are traversed by rents and fissures running parallel with the strike of the rocks,—generally N., or a few degrees E. of N.[3] These fissures, which vary in width from a few inches to several yards (at Mount Egerton the vein is 30 feet wide), have been filled with white, amorphous, drusy quartz, which splits into innumerable fragments. The veins are lined on either side by a few inches of clay, with iron-oxide and sometimes gold. There is a marked absence of fragments of the rock-walls in the veins, which consist of almost pure quartz. Gold is irregularly dispersed through the

[1] 'South America,' p. 237.
[2] 'Trans. Roy. Geol. Soc. Cornwall,' vol. viii. pp. 71, 124, 164.
[3] See Mr. R. Brough Smyth, 'Gold Fields of Victoria,' Melbourne, 1869.

quartz in grains, in ramifying filaments, and in rarer nodules. It also coats with a thin film some of the cavities and fissures—sometimes so thin as to show prismatic colours. As a rule, it is generally considered to be most abundant near the surface, and to decrease in quantity with the depth, though some of the veins are rich to depths of from 200 to 400 feet (see Fig. 177, p. 322).

Abnormal Conditions. Networks of rock-impregnations of ores are known as *Stockwerks* and *Fahlbands*. In the Erzgebirge of Saxony, the former are composed of a great number of very small veins of quartz, running in every direction, and interlacing with one another, through certain granitic and porphyritic rocks. These veins occasionally contain a little tin-ore, which is, however, more widely disseminated through the mass of the adjacent rock in almost imperceptible particles. In another instance the greater part of a granitic mass, 1000 to 1200 feet in diameter, is stanniferous; but the most productive portions are in nearly horizontal layers, or in layers concentric with the mass. In these cases the whole rock is worked together; nevertheless the proportion of metal is so small that the yield does not exceed ½ to 2 per cent. Some geologists consider these Stockwerks to be of contemporaneous formation with the rock itself, while others consider them as due to subsequent infiltration.

The 'Fahlbands' of Norway are zones of rock, varying from 20 to 1000 feet thick, impregnated with iron, copper, and zinc sulphides, together with a little lead and silver. The matrix is usually a crystalline schist and quartzite, of Cambrian or possibly Laurentian age; and the metal is in such fine particles as to be hardly visible. These metalliferous portions form belts or lenticular masses, ranging in the silver-district of Kongsberg for a distance of several miles. Owing to the prevalence of sulphides these masses decompose on exposure and form a disintegrated ferruginous surface easily traced. Here again some observers consider the impregnation of the fahlbands to have been subsequent to the deposition of the schists, and connected with the eruption of adjacent masses of gabbro; by others they are considered contemporaneous with the bedding. The importance of the fahlbands consists, however, not so much in the impregnated rock, as in the circumstance that it is usually only where the silver-veins of the district traverse these fahlbands that they are metalliferous. Between the other parts of the rocks the veins are generally barren. The lodes range E. and W., and traverse the fahlbands almost at right angles. The predominant ores are native and sulphide of silver, with the other metals before named, in a gangue of calcite, fluorspar, quartz, etc.

The mode of distribution of the tin-ore in the granite of Carclaze mine and in some of the elvans of East Cornwall agrees very closely with the Stockwerks of Germany, but we do not seem to have in this country any exact analogue of a Fahlband.

The Age of Mineral Veins. Rocks of Archæan and Palæozoic age are much more frequently traversed by mineral-veins than are those of Mesozoic age; and in the latter again they are more common than in strata of Tertiary age. Their frequency, however, appears to depend not so much on age as on the presence of metamorphic strata, and on the outbreak of plutonic and volcanic rocks. Nor must it be inferred because the lodes are found in strata of any particular period that this fact alone is evidence of their age. Mineral veins may traverse Archæan rocks and yet be of Tertiary age. Unless the rock traversed by any set of veins be overlain by strata of known age, and these are not traversed by the veins,—as, for example, the lead-lodes of the Carboniferous strata of Cumberland, which do not traverse the over-lying Permian strata,—or there be some other way of determining the age, the stratigraphical evidence fails; and this is a condition of not uncommon occurrence.

In these cases the only evidence to fall back upon is that dependent upon the disturbances with which the formation of the original faults and fissures is connected. This evidence is not perfectly satisfactory; still it is one which may serve as a guide. Mineral-veins occur most frequently in groups running in lines, which are generally parallel to the strike of the axis of elevation of the adjacent mountain-range; so, if the age of the latter is known, that of the former may be inferred. There are limits, however, to the extension of this synchronous parallelism, although those limits may, as in the case of the parallel folds and corrugations of some of the early crystalline schists, extend over very wide areas.

The nature of the lode gives little clue to its age; still certain minerals seem to have predominated more at one period than at another; as, for example, tin-ores are generally confined to the older so-called plutonic and metamorphic rocks; copper and argentiferous lead-ores are abundant in the same rocks; lead-ores are also especially common in the limestones of later Palæozoic and Secondary age; while gold has a wider range from Palæozoic to Tertiary strata; but no definite law can be laid down.

Veins of Palæozoic Age. The E. and W. tin- and copper-lodes of Cornwall are certainly anterior to the Trias, and possibly to the Permian. But if, as before suggested, there were granitic centres older than the Carboniferous period, then it is possible that there may be lodes of pre-Carboniferous date. The N. and S. courses, with their lead- and iron-ores, traverse rocks of Carboniferous age; and cannot therefore be otherwise than post-Carboniferous, and pre-Permian or pre-Triassic.

The age of the lead-lodes of Cumberland is more clearly defined, since, as before said, they lie in Carboniferous strata, and do not traverse the overlying Permian strata. The lead-lodes of Derbyshire are probably of the same pre-Permian age. The lead-lodes of North Wales and of the border counties are also known to be of the same post-Carboniferous age.

A large number of the mineral veins of Europe, such as most of those of Norway and Sweden, the celebrated lead- and silver-mines of Freiberg; the copper- and lead-mines of Silesia and of Bohemia, and many of the copper and argentiferous lodes of Southern Spain, are in gneisses and crystalline schists of Laurentian or Archæan age; but to what particular period of Cambrian or later Palæozoic age they are to be referred, superposition affords no evidence. Cotta, however, on the strength of the presence in the Roth-liegende of boulders of a peculiar porphyry, which he considers of post-Carboniferous age, refers, but with some hesitation, the principal Freiberg lodes to Lower-Permian age.

The silver-mines of Andreasberg in the Hartz, the quicksilver-lodes of Spain, the argentiferous lead-lodes of Brittany, and the lead- and silver-lodes of Przibram, are in strata of Silurian age; while in the Rhenish Provinces iron, lead, silver, nickel, and other lodes traverse rocks of Devonian age.

The Carboniferous rocks are often rich in mineral-veins. The lead-lodes of the Hartz traverse sub-Carboniferous as well as Devonian strata; and, as they do not penetrate the overlying Permian strata, their age is pretty clearly defined, and may be synchronous about with the close of the Coal-measure period. The iron-lodes of the Thuringian Forest are of post-Permian age.

Veins of Secondary Age. The silver- and copper-lodes of the Tyrol traverse the Muschelkalk. Cotta[1], however, considers that the argentiferous lead-lodes of the Thuringian Forest, as well as those of Saxony, of the Morvan in Central, and of the Department of the Aveyron in Southern, France, immediately followed on the deposition of the Lias.

The lead-, silver-, copper-, cobalt-, and antimony-lodes of the Black Forest are of Jurassic age; as are also some of the auriferous quartz-veins of the Alps.

The Upper-Cretaceous strata of Westphalia are traversed by veins of galena and blende; and the copper-lodes of Tuscany are associated with serpentine, the outburst of which seems to have immediately preceded the Tertiary period; but, as a rule, mineral veins are rare in the Cretaceous rocks of Europe.

Veins of Tertiary Age. The gold-lodes of Western Transylvania, the lodes of auriferous pyrites with silver, lead, and copper ores of Northern Transylvania, and the veins of silver, lead, and pyrites (with little gold) of Schemnitz in Hungary, are connected with the outburst of trachytic rocks through strata of Eocene age.

The auriferous quartz-veins of the Ural mountains traverse granitic and schistose rocks without any superimposed strata. From the circumstance however that the Permian conglomerates on the western flanks of

[1] *Op. cit.* pp. 364-8.

the Urals contain materials derived from Silurian strata before the elevation of that chain of mountains, and that in those conglomerates there is débris derived from the copper-lodes of that older Silurian area, whereas there is no trace of débris derived from any gold-veins, Murchison concluded that at the Permian period the copper-lodes already existed, and that the gold-veins were of later age. He considered that their origin dated from the last disturbance to which the elevation of the Urals was due; and to this he assigned a very recent date. He concluded, in fact, that in this region 'gold was one of the most recent mineral productions anterior to the historic area.' But the American geologists have shown, in the case of the Pacific border ranges, that evidence of this character is not always to be relied upon. Still, the nearly meridional direction of those mountains agrees better with the System of Tenara (Quaternary) than with that of the Cote d'Or (Jurassic), to which the last upheaval has been assigned.

Their Relation to Periods of Disturbance. In South America the great mineral-veins are in close relation to the major lines of disturbance. Darwin pointed out their connection with the axes of the Andes in South America; and it is possible that they are of as many dates as there are periods of disturbance; but the subject requires further working out. The veins traverse rocks of all ages from Palæozoic to Tertiary times.

In North America the evidence is clearer, though it still leaves much to be desired. To take as an instance that most remarkable district—the chains of the Cordilleras of California. The trend of these chains is from north to south, and the strike of the great faults and of the mineral-veins is in the same direction. Two epochs of disturbance have been established. One culminated in the Jurassic period, and is in all probability the dating point of the large class of lodes that are met with in granites and in various sedimentary rocks ranging in age from Archæan and Palæozoic to the Jurassic period. The silver-bearing lodes of the White-Pine district are in strata of Devonian age; and those of the Humboldt district in Triassic strata; while the auriferous quartz-veins of California are mainly in strata of supposed Jurassic age.

The second group of mineral-veins is that which is connected with the great outbreak of igneous rocks during early Tertiary times. It embraces many important veins in Mexico and the great Comstock silver-lode of the Nevada. This wonderfully productive group of mineral-veins is anterior in geological time to the series of great volcanic outbursts which are considered to be of post-Miocene age.

But, although the general elevation of the chains of the Cordilleras took place during the Jurassic and Tertiary periods, it is impossible to say how far the veins in the older rocks belong to these periods of disturbance.

Sometimes the veins have been twisted and disturbed together with the strata; at other times they have remained undisturbed. The age of the enclosing rocks may be known; but data are too often wanting as to the age of the formation of the fissures themselves [1]—a remark which will equally apply to a considerable proportion of the mineral-veins of the Old World.

[1] Clarence King, 'Exploration of the Fortieth Parallel,' vol. iii. pp. 6–9, 37. A number of other important works on the mining districts of America have recently been published by the U. S. Survey.

CHAPTER XIX.

METALLIFEROUS DEPOSITS (*continued*).

ORIGIN OF MINERAL-VEINS. RELATION TO FAULTS. OPEN FISSURES. THERMAL WATERS. DRY FISSURES IMPOSSIBLE. THE STEAMBOAT SPRINGS. SULPHUR-BANK SPRINGS. THE COMSTOCK LODE. LODE-WATERS. LODE-MINERALS IN THERMAL SPRINGS. ARTIFICIAL PRODUCTION OF VEIN-MINERALS. DE SENARMONT'S AND DAUBRÉE'S EXPERIMENTS ON SILICA, SILICATES, &c. REACTION OF THERMAL SPRINGS ON SOME EARTHS AND METALS. DAUBRÉE ON THE WATERS OF PLOMBIÈRES AND BOURBONNE. THE GENESIS OF LODES. THE TIN-GROUP. THE LEAD AND SULPHIDE GROUP. IRON-OXIDES. THE RARER NATIVE METALS. IRREGULAR AGGREGATIONS; GELLIVARA; DANNEMORA; FAHLUN; FABERZ; RAMMELSBERG; ELBA. ZINC MINES; AIX-LA-CHAPELLE. RED HEMATITE; ENGLAND; NORTH AMERICA; CANADA. EFFECTS OF WEATHERING ON THE LODES. GOSSAN. OXIDISATION AND REDUCTION. STRATIFIED ORE-DEPOSITS. WIDE DISPERSION OF THE METALS. CARBONIFEROUS ORE-DEPOSITS: THEIR ORIGIN. PERMIAN AND TRIASSIC ORE-DEPOSITS: THEIR ORIGIN. CHESSY. JURASSIC ORE-DEPOSITS. CRETACEOUS ORE-DEPOSITS. RECENT ORE-DEPOSITS. ORE-BEARING DRIFT DEPOSITS; TIN; GOLD.

Origin of Mineral-Veins. The instances given in the last chapter serve to show the close relation existing between mineral-veins and faults; but, while faults are not limited to any particular region or strata, mineral-veins are confined to certain areas of disturbance and to centres of eruptive and metamorphic rocks; and, while faults are accompanied by displacements of level often of enormous magnitude, mineral-veins generally show comparatively little displacement of the strata, and are sometimes mere rents or fissures in the rocks, without change of level of the enclosing walls. It will be observed also that in ordinary faults the spaces between the walls have been at once closed, whether by great lateral pressure, or by the débris resulting from the friction of the side walls; whereas in the case of fault-veins, the side walls left irregular unfilled spaces, or else rents or fissures were formed which must for a time have remained altogether open.

Into these cavities and fissures mineral matter and metallic ores have been subsequently introduced. By Werner and his school they were supposed to have been introduced in a state of solution from above; by others they were supposed to have been injected, simultaneously with the opening of the fissures, from below; but the more general opinion

of geologists now is, that they are the deposits formed during lengthened periods by thermal mineral waters or by sublimation. The objection to open fissures which would seem to have had most weight with many experienced observers is the fact that there are mineral-veins inclined at an angle of 45° or even less, the walls of which are in many cases so soft and yielding, that it seems difficult to conceive that they could remain open for any time without the fall and closing in of the walls.

But the softness of the enclosing strata is generally due to decomposition subsequent to the formation of the fissure; and, in the case of these inclined veins, where they are accompanied by dislocation and shifting of the strata, the harder and projecting portions served as pedestals to support the hanging wall. The nearer the rents approach verticality, the more regular and open they have remained. The famous lode of Andreasberg has been followed in a sheer perpendicular descent to the depth of 2500 feet, and in a linear direction on the surface for a distance of about 2000 feet, while the walls of this great fissure are never more than 4½ feet, or less than 1 foot apart. Where, on the other hand, the vein is inclined, and passes through strata of variable resistance, the more irregular become the walls of the fissure, as also the lode (Fig. 174).

There is evidence also that the rents have often been enlarged and the levels of the walls shifted at different times. In 'combed' veins (Fig. 169, p. 313) the difference in the successive layers of minerals show that the thermal waters underwent a series of changes due probably to some alteration in the dimensions of the fissure. The gangue or veinstones in fact not unfrequently show secondary planes of fracture and slickensides.

The extent of throw, when there has been any, cannot always be determined. In Cornwall, as before mentioned, the lodes frequently seem to be unattended by any changes of level of the enclosing walls, or else by only a very small vertical change. Even in the fault-veins of Cumberland the throws are commonly small; none exceeding 260 feet. It is probable that faults of great throw or much lateral pressure, especially where the dip is small, would be accompanied by so much squeezing and such an amount of wall-débris as to plug and close the fissure at the moment of its formation, and prevent the subsequent introduction of mineral matter.

Ordinary mineral-veins were no doubt fissures in which there were cavities or spaces left open for a length of time, and in the interstices or on the sides of which were gradually deposited a variety of minerals and of metallic ores. The banded structure of some veins, and the fact that the minerals are such that could be deposited in water, tend to prove that their formation has been in most cases due to thermal waters, rather than to sublimations of gases and vapours such as are now discharged in the solfataras of volcanic districts. It is possible that in some instances such emanations may have contributed to a particular result, but in the

majority of cases the phenomena agree better with the hypothesis of aqueous solution.

Dry fissures impossible. Besides, although we may have dry fissures on some high grounds or mountains, it is not possible that such could have existed under the ordinary prevailing conditions of the land and rainfall. For it follows from what we have before said, in the chapter on Springs and Underground waters, that the surface-waters fill, and always must have filled, all porous strata and all open cracks and fissures below a certain level—that level being regulated by the sea-level on the coast-lines, and by the level of the streams and rivers inland. Consequently rents or fissures formed in any past geological periods must, as now, have inevitably been filled with the water held in, or percolating through the sedimentary strata, or through the cracks and crevices of the crystalline rocks, up to the level of the underground water-line of the district,—a line rising with the distance from the coast, but never sinking

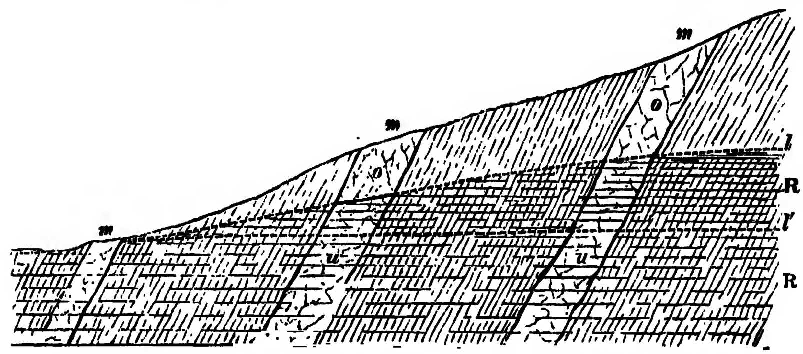

FIG. 180. *Diagram showing the position of the Water-Level in the Veins and Fissures of a Mine.* *R.* Encasing Rock. *m.* Mineral Veins—*o.* oxidised; *u.* unoxidised, portions of the vein. *l.* Line of variable water-level. *l'.* Line of permanent saturation.

below it. The above diagram is supposed to represent the side of a river-valley in a mining district. Where little rain falls *l'* is more dependent on the more distant sea-level.

Further, owing to the depths of the fissures, and the increase of temperature with depth, the water at the bottom becomes exposed to much higher temperatures than at the surface, and this gives rise to convection currents, which establish a constant circulation, and thus serve to keep up a constant renewal of the mineral matter in solution from deep-seated sources.

The 'Steamboat Springs.' Mr. J. A. Phillips has described[1] a remarkable group of parallel fissures, seven miles west of Virginia City, Nevada State, from which issue thermal waters still depositing mineral substances analogous to those forming mineral-veins. The whole district

[1] 'Phil. Mag.' for 1868, p. 321, and for 1871, p. 401. See also Clarence King, *op. cit.* vol. ii. p. 825; and Le Conte in 'Amer. Journ. Sc.' for June, 1883, p. 424.

is one in which volcanic agency has been rife at no very distant period, and abounds in geysers and hot springs. The 'Steamboat Springs,' as they are termed, lie in a granite valley about 5000 feet above the sea-level, with hills on either side capped by basalt. The rock is traversed by numerous parallel fissures running N. and S., and extending altogether 1160 yards in nearly straight lines. The fissures are in great part filled up with a deposit of silica, and the water issues from narrow crevices at separate vents in a linear series. Around these vents the water has deposited low siliceous mounds, which at their base merge into one another. West of these springs another set of fissures pass through the siliceous crust, but the water in them rises only to within 7 or 8 feet of the surface, where it can be seen and heard in violent agitation owing to the escape of steam and carbonic acid. The five largest of these fissures, which are about 25 feet apart, are at least half a mile long, apparently 20 to 30 feet deep, and 1 foot wide. The edges are ragged.

The water of these springs is alkaline, and contains carbonate of soda, with sodium chloride and sulphide. Everywhere carbonic acid is evolved, and at places sulphuretted hydrogen. A deposit of hydrous silica lines the fissures to the thickness, in places, of several feet. This has formed a series of semi-crystalline bands, like the combed bands of a mineral-vein, with which some iron-oxide and sulphur have been also deposited. The continued overflow of these springs has covered the granite, which is much decomposed, with a thick deposit of siliceous sinter, so that the rock only shows in places. In the westward group of fissures the siliceous deposit contains iron- and manganese-oxides, with minute crystals of iron-pyrites and traces of copper, and, it is said, of gold. The silica shows both amorphous and chalcedonic structure, with small crystals of quartz in geodes.

Professor Le Conte states that at a short distance farther west thermal waters containing alkaline carbonates and alkaline sulphides came up, and probably are still coming up, carrying in solution and depositing in cooling sulphides of mercury and iron, which by oxidation give rise to a deposition of sulphur and the formation of sulphates of iron and alumina. The whole hill-side, which there consists of rhyolite, is decomposed by the acid vapours into a white chalky-looking earth, full of grains of quartz.

The very curious system of old quartz-veins, containing small proportions of vein minerals, which intersect the granite and granulite in the Morvan[1], present features singularly analogous to those of the hot springs just named. The white chalcedonic quartz which fills fissures in these rocks and forms an extensive layer or bed of quartz underlying horizontal

[1] 'Bull. Soc. Géol. de France,' 'Réunion Extraordinaire à Semur,' 1879, 3rd Ser. vol. vii. p. 890.

strata of Rhætic age, would seem to have been deposited by hot springs during the Triassic period. The layer is generally about 5 to 6 feet thick, but attains in places a thickness of 20 to 25 feet, and in one part rises, as it were, into a small mound. Sometimes the quartz is grey with black patches. In it there are dispersed some irregular modular masses of sulphate of barytes, geodes with fine crystals of fluor-spar and imperfect rock-crystals, small crystals of galena and spots of azurite. The annexed is a section taken near Avallon.

FIG. 181. *Section at Le Brouillard.* (C. Velain.)
a. Surface soil and drift. *b.* Rhætic (Infra-lias) strata with *Avicula contorta, Lima Valoniensis*, etc. *c.* Layer of vein-quartz. *d.* Light sandstone with black stains. *e.* Granite.

There can be little doubt of the hydro-thermal origin, and of the issue through fissures, of this mass of silica. It extends over a considerable area.

'Sulphur-Bank Springs.' Another remarkable group of springs, presenting an interesting case of modern mineral deposition and also apparently of sublimation, are the 'Sulphur-Bank Springs,' in the coast range of California, 100 miles north of San Francisco. The region consists of much disturbed Tertiary (Miocene) strata with volcanic outbursts of Pliocene date. The bank is a low rounded hill, on an eastern bay of Lake Clear, formed by an old lava-flow overlying sandstones and shales inclined at high angles. The surface consists of snow-white pulverulent silica, the residue of the decomposition of the volcanic rock by the solfataric waters. Deeper down the rock becomes sounder, consisting of rounded masses of andesite surrounded by a white ashy earth, and then passes into a solid jointed rock. Sulphur is found in abundance, and often in beautiful crystals in the earthy mass between the blocks and in every crack. Mingled with the sulphur, cinnabar begins to appear, and goes on increasing in quantity with the depth, while the sulphur entirely disappears. Iron is very abundant near the surface as an oxide, and as pyrites at greater depths. Bitumen is found impregnating the rocks, and in small globules. The lower part of the solid lava-cap and the underlying sandstones are traversed by irregular cracks and fissures filled with a hydrous silica (opal) in a soft cheesy condition, and nearly always streaked and clouded with cinnabar. At a greater depth a mud and rubble water-way was met with, from which rose hot alkaline waters, charged with sulphhydric, carbonic, and boracic acids, with some alkaline sulphides. This brecciated bed is rich in cinnabar (at places containing as much as one half), mixed with iron-pyrites. The temperature of the water is 160° F. The same bed or fissure has been found beyond the limits of the lava-stream,

and has there been worked for cinnabar. 'Here, then,' Professor Le Conte observes, 'undoubtedly we have still forming under our eyes mineral-veins with quartz, vein-stuff, and metallic ore[1].'

In many mines the water which issues from the lodes is hotter than that of the surrounding rock (*country*). This may sometimes arise from the decomposition of the lode through which the water passes; but it is in most cases independent of this cause, and is due to the rise of the water from greater depths, like thermal springs on lines of fault, through crevices in which the deeper subterranean waters are driven upwards by hydrostatic pressure.

The Comstock Lode. In working this celebrated lode to its present great depth, hot springs have been successively tapped[2], issuing from the vein, and following in all probability in sequence upon those to which the vein itself owes its origin. From the surface down to a depth of 700 feet, the temperature of the lode-water was from 70° to 75° F., or only a few degrees above that of the enclosing rock, whereas at the depth of 1200 feet the water had a temperature of 108°; that of the rock is not given. At the ordinary rate of increase from the surface it would only be 85° to 90°. On one occasion, on tapping one of these lode-springs, the water rose 100 feet in the shaft.

The later observations of Mr. Church[3] show that at a depth of 2000 feet the water from the lode had a temperature of above 157° F. He attributes this high temperature not to subterranean heat, but to the heat produced by decomposition of the felspathic rocks. He points out also that there are belts of hot and cold ground, which he accounts for by differences in the decomposition of the rock. It seems to me more probable that these differences are caused by the direct infiltration of the surface-waters, which may in some parts of the lode affect the heated waters rising from depths more than in other parts. Lately another spring was tapped in the 2200 feet level which filled the mine to the 1700 feet level,—the water rising a height of 500 feet. This body of water had a temperature of 150° Fahr.

Lode Waters. The analysis of one of the Comstock Lode springs gave the following result, which shows a large proportion of mineral matter compared with a spring in a Cornish mine. But it must be borne in mind with respect to the Cornish waters, that the lowering of the subterranean water-level by pumping at depths causes in many cases, even at some distance from the coast, a reverse flow (*ante*, p. 164) by which sea-water, as apparently has been the case in this instance, may be introduced, and thus alter the normal condition of the lode-water.

[1] 'Amer. Journ. Science' for July, 1882, and June and July, 1883.

[2] C. King, *op. cit.* vol. iii. p. 86.

[3] 'Trans. of the Amer. Inst. Mining Eng.' for 1878.

Contents per litre.	Comstock Mine, 600 feet level. (Clarence King.) Grammes.	Balleswidden Mine, 300 feet level. (J. A. Phillips.) Grammes.
Silica	·0305	·0100
Alumina and Ferric Oxide	·0009	tr.
Chloride of Sodium	·0021	·0735
Sulphate of Lime	·5044	·0970
Sulphate of Magnesia	·0308	chloride tr.
Carbonate of Potash	·0148	chloride ·0135
Carbonate of Soda	·1297	——
Carbonate of Magnesia	·0512	——
Carbonate of Iron	——	·0022
Carbonic Acid	——	tr.
	·7644	·1962

Lode Minerals in Thermal Springs. With the exception of silica and a small quantity of iron, neither of these waters contains in solution the minerals which go to form veinstones and lodes. But there are some mineral springs, or the deposits from existing springs, which show the presence of many of the more ordinary constituents (*a* in the following table); and although the quantities of these substances are now, in all cases, reduced to a minimum, they serve to indicate the agencies which were once at work on a larger and more active scale.

Salts, in Grammes per litre.	Schwollen, Duchy of Oldenburg. (*Kastner.*)	Golaise, near Geneva. (*O. Henry.*)	Baden. (*Loenig.*)
a. Silica	0·25 5 }	0·0360	0·0009
Alumina	0·14 6 }		
a. „ phosphate	0·00 5	0·0100	0·0009
a. Lime carbonate	0·99 5	0·1436	0·3387
„ sulphate	......	1·3700	1·4142
Calcium sulphide	......	0·0786	......
a. „ fluoride	0·0005	......	0·0021
„ chloride	......	......	0·0936
Magnesia carbonate	0·6415	0·0589	0·0199
„ sulphate	......	0·2900	0·3180
Magnesium chloride	......	......	0·0737
a. Barytes carbonate	0·0015	......	......
a. Strontian „	0·0012	......	0·0007
Lithia „	0·0225	......	......
Lithium chloride	0·0010	......	......
Soda carbonate	1·8750	......	......
„ sulphate	0·1465	......	0·2980
„ phosphate	0·1185	......	......
Sodium chloride	0·5115	0·0[illegible]70	1·6982
„ bromide	0·0011	......	......
„ iodide	0·0165	......	......
Potassium chloride	0·1225	......	0·0926
a. Iron carbonate	0·4925	......	......
a. „ sulphide	......	0·0200	......
a. Manganese	0·0018	......	......
Organic matter	0·0135	0·0180	......

M. Henry considers that in the Schwollen water the sulphide of iron is held in solution by the sulphide of calcium.

Later researches (Garrigou and Filhol) with the aid of the spectroscope have also detected in the thermal waters of Bagnères-de-Luchon, in addition to the ordinary more abundant salts and metals above named, the presence of *antimony*, *lead*, *bismuth*, and *copper*, held in solution probably by the alkaline sulphides. In other cases the solid matter deposited by two other mineral springs give still more positive results:—

	Deposit from the Sprudel Water, Carlsbad. (*Berzelius.*) *Grammes in 100 parts.*		Mineral spring of Alexis in the Hartz. (*Rammelsberg.*) *Grammes in 100 parts of the residue.*
a. Lime carbonate	96·47	*a.* Silica	13·62
„ phosphate	0·06	*a.* Lime	0·40
a. Calcium fluoride	0·99	Magnesia	0·12
Alumina phosphate	0·10	*a.* Iron peroxide	53·88
a. Strontian carbonate	0·30	*a.* „ protoxide	6·95
a. Iron oxide	0·43	*a.* Manganese peroxide	1·68
a. Manganese oxide	tr.	*a.* Arsenic	1·36
a. Tin oxide	0·06	*a.* Copper	0·02
Water	1·59	Water and organic matter	23·93
	100·00		101·96

Here then are instances of *silica*, *lime*, *strontian*, *barytes*, *calcium*, *fluorine*, the essential constituents of veinstones, together with lode-metals, comprising *antimony*, *iron*, *manganese*, *tin*, *lead*, *copper*, *bismuth*, and *arsenic*, occurring in solution in mineral waters. The solvents may be either the alkaline carbonates or the sulphides, one or other of which are commonly present in thermal springs. In twelve of the thermal waters of France and Savoy the proportion of sulphide of sodium present varies from 0·0105 to 0·0690 gramme per litre.

That metallic ores, insoluble under ordinary conditions, may nevertheless be taken up and re-deposited even by surface-waters, is shown by the fact that oxide of tin has been found in the sub-fossil bones of deer (red?) in the stream tin-beds of Cornwall[1]; while in Germany the sulphide of lead has been found forming, with fragments of elephants' bones, a breccia filling crevices on the outcrop of some mineral veins[2]. Again, Mr. D. Forbes obtained from a fissure in the Corocoro mine of Peru the fossil bones of an extinct mammal of late Pleistocene age allied to the existing llamas; and it was discovered that the haversian canals of these bones were for the most part filled with threads of native copper[3]. These are no doubt cases of reduction following on the decomposition of adjacent vein-lodes.

The general conditions under which the contents of veins were deposited would be however very different from those which obtain in these surface-waters. Great heat and pressure effected re-actions impossible in

[1] J. H. Collins, 'Trans. Roy. Geol. Soc. Cornwall,' vol. x. p. 98.
[2] Credner's 'Traite de Géologie,' p. 390.
[3] 'Quart. Journ. Geol. Soc.,' vol. xvii. p. 74.

our laboratories. Nevertheless, although we cannot imitate the powerful laboratory of nature, we can obtain artificially results which give a clue to some of its processes.

Artificial Production of Vein-minerals. Silica, when deposited above ground from alkaline solutions by hot springs, forms a white amorphous and hydrated substance, and rarely crystallises or possesses crystalline properties; whereas at depths, under heat and pressure, it becomes crystalline or crystallises. M. de Senarmont [1] showed in a series of beautiful experiments, made many years since, that silica, placed artificially in a like state of solution, deposits under pressure and at a temperature of from 200° C. to 300° C. (392° to 572° F.) very minute crystals of quartz. He also, by exposing various earthy minerals and metallic oxides and sulphides to the action of bicarbonate of soda at temperatures of from 150° to 250° C. and under pressure, succeeded in obtaining minute crystals of sulphate of barytes, carbonates of magnesia and of iron, and of fluor spar, together with the sulphides of iron, antimony, zinc, copper, etc. By analogous processes he obtained various amorphous and anhydrous precipitates, including iron-peroxide and the sulphate of lime.

M. Daubrée [2] obtained similar results by subjecting glass to the action of water at a temperature estimated at about 400° C. (852° F.), and under a pressure of more than 1000 atmospheres. The glass was rapidly decomposed, and a large proportion of its silica set free; and at the end of a month innumerable colourless pyramidal crystals of silica about 2 millimètres long were formed in the enclosing tube. M. Daubrée detected in the decomposed glass microscopic dark-green crystals of pyroxene (var. *diopside*), and a number of siliceous microlites. Fragments of obsidian and perlite, subjected to the action of superheated water, gave analogous results; but vitreous felspar and oligoclase underwent no appreciable alteration. Fragments of wood (pine) were transformed into black masses, with a bright lustre, compact, and resembling anthracite; and so hard as to be with difficulty scratched by steel. The wood had the appearance of having been fused, forming small globules, difficult to burn, and, like the diamond, not conducting electricity.

Reaction of Thermal Springs on some Earths and Metals. Another series of observations of great interest, relating to the action of heat without pressure, has been made by M. Daubrée on the minerals formed naturally by the agency of hot springs on enclosing Roman masonry. These minerals are of a different class to those produced at depths, and are more analogous to those formed in volcanic rocks on the surface, or in the upper part of some lodes.

The hot alkaline waters of Plombières (Vosges) issue from a vein of

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[1] 'Ann. de Chim. et Phys.,' 3rd. ser., vol. xxxii. p. 129.

[2] 'Géologie Expérimentale,' vol. i. p. 154.

quartz and fluor-spar at a temperature of 158° Fahr. It was found that under the incessant action of these waters on the concrete, the cavities of the masonry and of the bricks had become lined with minute crystals, which on examination proved to be hydrated silicates (zeolites), and free silica in various states. Amongst these minerals, which occurred in well defined though minute crystals, were *chabazite*, *mesotype*, *apophyllite*, and a variety of *wollastonite*, together with an amorphous hydrated silicate of lime. The silica was generally hydrated and presented a mammillated opaline surface; but sometimes it was anhydrous with a chalcedonic structure. Scalenohedral crystals of *calcite* and acicular crystals of *arragonite* had also been formed. Similar changes were found by M. Daubrée to have taken place in Roman masonry at the hot springs of Luxeuil and in other such springs near Oran.

A different class of products was obtained from the thermal waters of Bourbonne, which have a temperature of about 150° Fahr., and rise through Triassic strata. The existing tank was built over an old Roman tank, which had become filled up with mud, sand, and vegetable matter (including innumerable nuts), intermingled in which there were remaining 4700 bronze, pewter, silver, and gold coins, together with a few bronze statuettes, pieces of lead frames, amber beads, a piece of jet, and some fragments of sandstone and flint. The long-continued action of the mineral waters (whose chief ingredients are alkaline chlorides and sulphates) on these materials had resulted in the formation of a number of minerals commonly found in lodes. The decomposition of the bronze had led to the formation of a black powdery *oxide of copper* and of well-defined crystals of *red copper*, of *grey copper*, and of *copper-pyrites*, comparable with the like minerals from the lodes of Redruth. A bronze tube was coated with the chloride of copper, and one of the coins with tin-oxide. The lead had formed a crust with minute crystals of galena, some small flakes of litharge, and a few crystals of the chloride and sulphate of lead. In another well at a short distance, lustrous iron-pyrites had been deposited on some flint flakes, and crystallised grains of the same were found in the quartzose sand. But while these researches bear upon the origin of some vein-minerals, they bear more especially on the changes subsequently effected by the weathering of the lodes (*postea*, p. 350).

There can be no doubt that under increasing pressure and temperature, underground alkaline waters must act with energy upon felspathic rocks and other silicates; and further that, in mineral veins, the water at depths rising surcharged with silica or with carbonate of lime, fluoride of calcium, sulphate of barytes, and other minerals, has deposited these substances, as the pressure and temperature became less nearer the surface, on the sides of the rents and fissures. The ribboned structure of the combed veins may be due to changes in the channels through which

the underground waters passed, brought about by successive slight disturbances affecting the enclosing rocks.

The Genesis of Lodes. It is more difficult, however, to understand the exact conditions under which the *metallic ores* were rendered soluble and originally carried into the lodes. Mineral veins have been divided, like the metals, into groups having certain characters in common. One has been termed the '*stanniferous group*,' confined chiefly to the oxides of tin and of titanium; the other, which has been termed the '*plumbiferous group*,' includes the large section of the sulphides of lead, iron, antimony, etc. (see Table, p. 9).

The Tin Group. M. Daubrée has shown that the presence of tin is intimately connected with that of quartz, and that after quartz certain other minerals foreign to ordinary lodes are likewise habitually present. These are silicates into which fluorine and boron enter, such as *tourmaline* and *schorl*, certain *micas*, *lepidolite*, *topaz*, *pycnite*, *axinite*, together with *apatite*, and other phosphates. He supposes that the tin was originally introduced into the lodes in the state of fluoride or boride—minerals stable probably only at high temperatures. It is possible also, that there were some combinations with phosphorus and chlorine. M. Daubrée observes, however, that it is difficult to define the nature of the reactions which take place at depths out of our reach, and which involve the formation of fluo-silicates and boro-silicates which we do not know how to form artificially. We only know the final term of a complicated series of changes. In this final term we have the oxide of tin associated with the minerals above named and with a portion of quartz,—minerals not brought up with the rock itself, but formed in all probability by the decomposition of the enclosing rocks under the influence of metallic vapours containing fluorine and boron [1]. It is to the action of these powerfully corrosive substances set free from their unstable combination with the accompanying metals, that M. Daubrée considers the decomposition of granitic and felspathic rocks so frequent in connection with tin-lodes to be due. The replacement of the felspar by pseudomorph crystals of tin-oxide in some of the granites of Cornwall, is another consequence of this form of metamorphic action. It may also be a question, considering the intimate and constant connection of quartz with tin-oxide, whether and to what extent silicon itself in its elementary state may have been concerned in these transformations.

The Lead and Sulphide Group. While *fluorine*, *boron*, *phosphorus*, and *chlorine* seem to have been the mineralising agents in the tin-lode group, *sulphur*, *selenium*, *tellurium*, and *arsenic* were the active agents in the lead-lode group. Although the characteristic minerals of the first

[1] *Op. cit.*, vol. i. p. 44.

group are absent in the second, quartz and fluor-spar are common in both. M. Daubrée and Dr. Sterry Hunt both incline to the belief that the metallic sulphides either came up originally in the state of soluble sulphates, which were (as in the Bourbonne waters) subsequently reduced; or else that they were held in solution by alkaline carbonates and sulphides. Small deposits of the sulphides of lead and zinc are not uncommon in crevices of septaria and ironstone-nodules occurring in various sedimentary strata, in which cases the metal must clearly have been introduced in a soluble state, and reduced after the segregation of the containing bodies; but it is doubtful if this mode of origin can be ascribed to the sulphurets formed at depths under great pressure and heat. As the metallic sulphides are found to exist in the deepest parts to which the lodes have been followed, all that at present can be affirmed is, that this points (whatever may have been the original menstruum) to a normal condition of deposition, and that these minerals have undergone no subsequent changes except those, presently to be noticed, resulting from oxidisation where the vein comes to the surface.

Iron-Oxides. Spathic iron-ore and red hematite, common in many veins, may often be due to the reaction of heated waters on the chloride of iron,—the chloride of iron, when exposed to the action of the vapour of water, being decomposed, with the production of hydrochloric acid and iron-peroxide. The products of these reactions are common in volcanic districts.

The rarer Native Metals. The few scarce metals, which do not enter into combination with sulphur or with any other non-metallic substance, form a class apart, whose origin is still somewhat obscure, for, like the diamond, they are difficult to trace to their source. Platinum, palladium, iridium, rhodium, and osmium are found native, generally in drift gravel, and often in association with gold. But, unlike gold, they have been very rarely found in lodes, and then only in very small quantities. There is reason to believe, that, like the chromate of iron, these metals are connected with erupted serpentinous rocks; for in some of these rocks they have been occasionally found irregularly disseminated [1] in small grains, which only in rare cases attain the size of nuggets. One of the largest, if not the largest, mass of platinum is a Russian specimen weighing twenty-one pounds troy.

Irregular Aggregations. These constitute a class of ores difficult to define. They are not lodes, and they are not, like the common clay-ironstone, concretions segregated in soft sedimentary strata; or, like the ferruginous marlstone of the Lias or the iron-ores of the Oolites, ordinary contemporaneous sediments or precipitates, more or less changed.

This class of ore-deposits consists chiefly of great lenticular or ramifying masses of metallic oxides and sulphides, of frequent occurrence in crystalline schists of Archæan or Palæozoic age, and occasionally met

[1] Murchison, 'Russia in Europe,' p. 484.

with in Triassic and even newer strata. These masses are sometimes closely connected with contemporaneous erupted rocks; but at other times they seem to have been the effect of subsequent metamorphic action or segregation, or else are chemical precipitates.

The magnitude of some of these masses, in which iron-ores largely predominate, is very striking, far exceeding that of any vein-lodes. Amongst the most remarkable in Europe are those of Norway, Sweden, and Elba. At Gellivara in Sweden magnetic and specular iron-ores, enclosed in and interlaminated with hornblendic and quartzose rocks, form a bold hill. Several of the ore-beds are from 100 to 200 feet thick, and have been traced for a distance of from 600 to 700 yards. The celebrated mines of magnetite of Dannemora form an irregular belt, 1½ miles long, in crystalline limestone and petrosilex. The workings in this mass extend to a depth of more than 600 feet. At Arendal elongated masses, from 6 to 20 feet and in places 70 feet thick, of magnetite subordinate to hornblendic and micaceous schists, extend for a distance of about 13 miles in a direction, as a rule, parallel to the foliation of the containing rocks [1].

Some of these lenticular masses, with their irregular ramifications, are shown in the accompanying ground-plan.

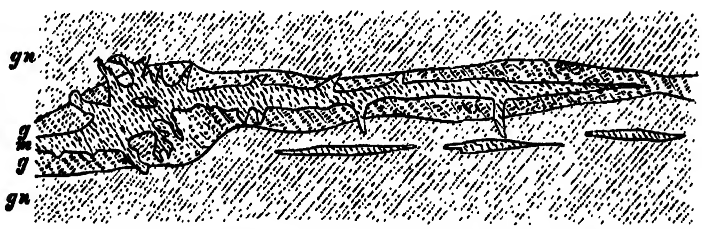

FIG. 182. *Section of the Lenticular masses of Magnetite in Arendal Mine.* (Cotta.)
gn. Gneiss. *m*. Magnetite. *g*. Altered rock.

The central core here is a pure magnetite, while in the crust or shell it is mixed with a number of minerals, some peculiar to it and others common to the enclosing gneiss. Anthracite occurs in the gneiss outside the mines; and the whole is traversed by granite dykes.

At Fahlun segregations of copper- and iron-pyrites, with grey quartz, in mica-schist and gneiss form broad lenticular masses, thinning out on all sides. Native lead and native copper occur associated with the peroxides of manganese and iron in the dolomites, intercalated with felsites and subordinate to gneissic rocks, at Paisberg in Sweden [2].

At the mines near Schmiedeberg (Fig. 183), the magnetite occurs in lenticular masses or lenses parallel with the rock surfaces, between the

[1] Bauerman's 'Metallurgy of Iron,' 5th edit., pp. 60–64.
[2] Cotta, *op. cit.* pp. 447, 452–458.

gneiss and the granite, or in the gneiss, associated with hornblende and chlorite schists, granular limestone, etc.

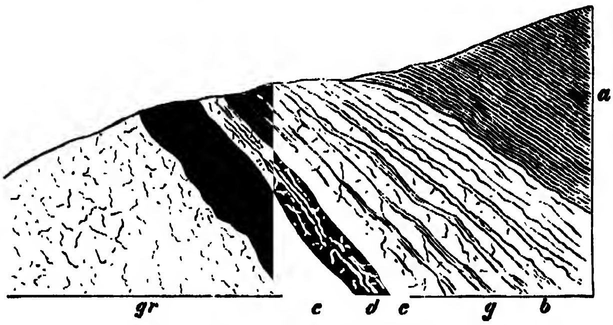

FIG. 183. *Iron-ore deposits near Schmiedeberg, Silesia.* (Von Cotta.)
a. Mica-Schist. *b, d.* Granitic Gneiss, etc., with seams or lenses of Magnetite. *c.* Hornblende-Schist.
gr. Granite.

Iron pyrites is of common occurrence; and the rocks are traversed by dykes of granite.

In Saxony and Piedmont large beds of magnetic iron-ore, in association with copper- and iron-pyrites, occur in talcose schists and dolomites.

At Faberz magnetite is met with in small strings and lumps in a porphyritic rock (greenstone or diorite); and in the Urals it occurs in a vast mass in a doleritic porphyry, forming a ridge 600 yards long, 500 yards broad, and about 250 feet high, made up in great part of pure magnetic ore. This ore, rare in England, forms a small band 1 foot thick, over diorite near Brent, Devon; and near Penryn it forms a lode about 3 feet thick.

A. *First Section.* B. *Later Section.*

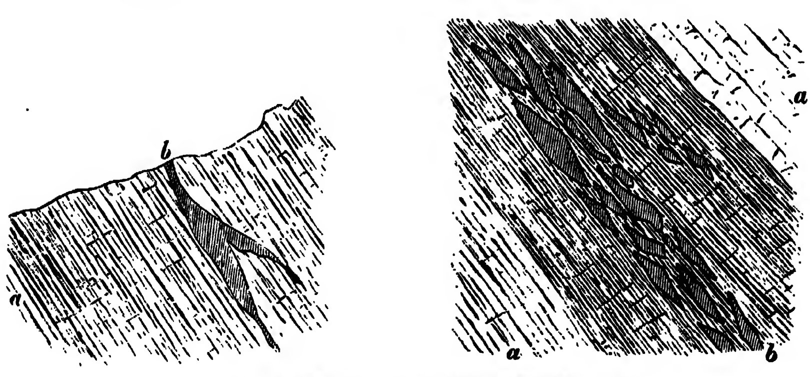

FIG. 184. *Section of the great Rammelsberg Copper Lode, Hartz.*
a. Clay-slates and Schistose Rocks. *b.* Ore-beds.

An illustrative instance of a segregated deposit, consisting of a mixture of iron- and copper-pyrites, galena, blende, mispickel, etc., associated with

heavy spar and a little quartz and calcite, occurs in argillaceous slates of Devonian age at Rammelsberg in the Hartz. Originally the principal vein, which is about 1900 feet in horizontal length, 800 in depth, and 150 feet in thickness, was supposed to form one whole, A, Fig. 184[1]; but later researches render it probable that it consists of a number of small lenticular masses separated by thin seams of schist, and lying in the planes of bedding (B, Fig. 184). A banded texture in the masses of pyrites has been often recognised, running parallel to the bedding. The enclosing schist contains fossils converted into pyrites[2]. Cases analogous to this, and to that at Fahlun, are those of the copper deposits of Agorda in Triassic strata, of Rio Tinto in Silurian clay-slates, and some others.

Elba presents a remarkable and well-known instance of an immense mass of specular-iron, hematite, and magnetite, with occasional fragments of the enclosing rocks, lying in strata of crystalline dolomite and mica-schist, dipping at a high angle and broken through by eruptive diorite and serpentine. The age of the rocks, which are strongly metamorphosed, is uncertain. They have been referred to Palæozoic strata; and, on the other hand, they have been considered to be so recent as Tertiary. The iron-ore forms a wedge-shaped mass, some 100 feet thick, and 350 feet high; and the mode of injectment or deposition is still an unsettled question. By some these metallic masses are considered to have been injected; by others to be the result of sublimation. The rocks in contact show metamorphic action similarly as with igneous rocks.

Zinc-ores also occur in isolated masses. The great calamine (Zn, CO^2) mine of Aix-la-Chapelle, worked to open day, is in a mass estimated at 1300 feet in length and 500 to 650 feet in width. It is mixed with mottled clays and oxide of iron, and contains, at the points of contact, angular fragments of the enclosing rocks, which are of early Carboniferous age.

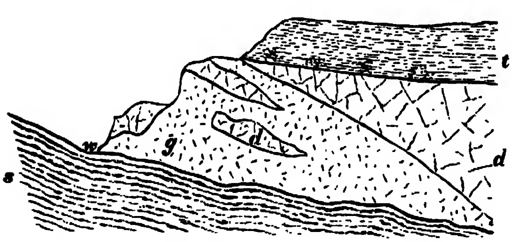

FIG. 185. *Section of the Zinc-ore Quarry at Scharlei, Silesia.* (Cotta.) *t.* Tertiary strata. *s.* Limestone floor. *d.* Dolomite. *g.* Red Smithsonite, with enclosed masses of Dolomite, and with a thin layer of white ore at base, *w.*

Another mass of zinc-ore is worked in the Muschelkalk at Scharlei in Silesia (Fig. 185). It is 110 feet thick, by 1750 feet long, and 190 feet wide, and here consists of a red smithsonite (a hydrated silicate of zinc) mixed with much peroxide of iron, and traversed by irregular strings of galena. It contains blocks of the overlying dolomite. The superimposed Tertiary strata contain at their base derived fragments of galena.

[1] Whitney, *op. cit.* p. 47.
[2] Cotta, *op. cit.* p. 161.

The Zechstein of the Thuringian Forest contains some very anomalous masses of iron-ore. They are irregular in form, and evidently consisted originally of spathic iron, which has been altered from the surface into limonite. They are apparently connected with the intrusion of granite through a cellular limestone (Rauchstein), the Rothliegende, and the Bunter Sandstone. The masses are associated with and often surrounded with heavy-spar. The iron-ore has also penetrated hollows in the limestone.

In this country red hematite occurs in independent cavities and pockets of the Carboniferous Limestone near Bristol. In Cumberland it forms an irregular bed from 15 to 60 feet thick, lying between a shale floor and a limestone roof; and in Flintshire it occurs as a breccia of angular fragments cemented by calcite, filling large irregular cavities or fissures in the Carboniferous Limestone[1].

The Archæan rocks of North America contain some extraordinary masses of iron-ore. Amongst the most extensive of these deposits are those in the Lake Superior district. They there help to form literally mountain-masses in the Huronian rocks. The ore is mainly a pure peroxide or specular-iron. In places a little magnetic oxide is mixed with it; sometimes in fine crystals. These ores are found at intervals in a belt of slates from 6 to 25 miles wide, and extending for a distance of 150 miles[2]. In Missouri there are two hills—the Iron Mountain and the Pilot Knob—consisting in great part of iron-peroxide. Professor Whitney speaks of them as eruptive ores. The Iron Mountain, at the end of a ridge of reddish felspathic porphyry, is 200 feet high. Pilot Knob is 650 feet high, and consists of quartz-rock and specular and micaceous iron. It differs from the Iron Mo ntain in showing evident slaty structure.

In Canada, likewise, iron-ores abound. They consist chiefly of magnetic and specular iron, and form immense beds interstratified with gneiss and crystalline limestones, generally dipping at high angles. One bed, 25 feet thick, has been traced several miles; another is 100 feet thick; and one is a mass 200 feet thick. At St. Paul's Bay there is a bed of titaniferous iron-ore 90 feet thick.

From their alternation in the States and in Canada with chloritic and other schistose and gneissoid rocks, Professor Dana considers that these Archæan ores are metamorphic as well as the schists[3].

Effects of Weathering. The changes in the constitution of the lode-minerals caused by the action of the surface-waters are of very great interest. As most of the lodes, which crop out on the surface, are generally of a porous texture, and especially in that the amorphous vein-quartz is almost invariably drusy or extensively fissured and broken up, sometimes

[1] Bauerman, *op. cit.* pp. 67–69.
[2] Whitney, *op. cit.* p. 477.
[3] Manual, p. 74.

to the extent that it can be shovelled out like so much fine gravel or even sand, it is not surprising that the surface-waters pass through and find their way freely to considerable depths in the veins.

Continuous and maintained percolation can, however, only extend to the line of water-level established by the channels of escape on the surface, either on mountain-sides when on high ground, or on sea- or river-levels on lower grounds (Fig. 180, p. 336). The consequence is, that, whether it be in the high mountain mine-district of Peru, or the low hill districts of Cornwall, all veins show, above the line of permanent water-level, an oxidised crust of greater or less depth, in strong contrast with the unaltered deeper part of the lode; and as iron-pyrites is commonly present in a large number of lodes, its decomposition has resulted in the formation of hydrated oxides of iron, which give this portion of the lode an earthy or rotten (but at times consolidated) ferruginous character. This crust has received different names in different mining districts. In Cornwall it is called *Gossan*. It is there rarely more than a few fathoms thick; while, owing to the lower level of the permanent water-line in the higher mines of Przibram in Bohemia, the decomposition has extended to the depth of 350 to 400 feet; and in the mines of Peru and Bolivia it extends apparently to still greater depths.

This decomposition affects considerably the copper-veins of Cornwall. The normal ores at depths are copper- and iron-pyrites. Near the surface, these have been oxidised, the first stage resulting in the production of the sulphates of iron and copper, and the second being the liberation of the metallic oxides, effected by the presence of alkaline or earthy bases for which the sulphuric acid has greater affinity. In the case of the iron, this change follows rapidly on the first, but less rapidly with the copper, which is gradually washed as a soluble sulphate to lower levels, leaving most of the hydrated iron-oxide in the upper part, or the gossan. This is a common feature in all lodes,—so much so, that in some lodes in other parts of the world the upper parts of them are worked entirely for iron-ore, while deeper down they yield copper and other ores.

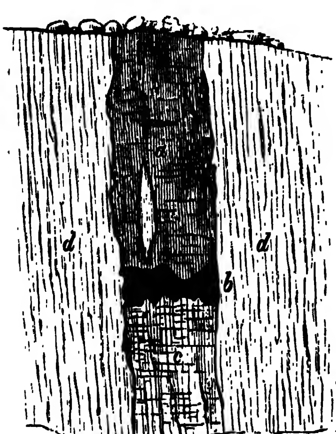

FIG. 186. *Section of an altered Copper Vein in East Tennessee, U.S.* (Whitney.)

Further changes, dependent either upon electrical conditions or on chemical reactions, have sometimes reduced the copper-salts, and led to the deposition of native copper; while at other times the red and grey oxides and blue and green carbonates of copper have been formed. A very interesting instance of these alterations is exhibited in a lode[1] which

[1] Whitney, 'The Metallic Wealth of the United States,' p. 322.

traverses micaceous and talcose schists (*d*, Fig. 186), of Silurian age, in Tennessee. The decomposition of the vein, which averages about 10 feet in width, extends to the line of water-level, and this varies, according to the height of the ground, from 20 feet to 90 feet below the surface.

The unaltered lode, *c*, consists of arsenical iron and copper-pyrites. These have been replaced in the *gossan*, *a*, by iron-oxides and consolidated fragments of the ferruginous veinstone, while between the two, at *b*, is a mass 2 to 3 feet thick of black copper-ore (red and black oxides), with some native copper and green and blue carbonates. On the top of the ground are blocks of the veinstone left by the degradation of the surface.

In the same way, lead-lodes, of which the unaltered deep parts consist of galena, are changed near the surface into carbonate, phosphate, and sulphate of lead. The change into carbonate may be effected so rapidly that it is sometimes found to have taken place in the old surface rubbish-heaps containing galena of a few years' standing.

Native silver has been often reduced from the sulphide. It is occasionally found in the *gossan*, with, in a few instances, traces of gold, in some of the Cornish lodes. The great silver-lodes of Mexico, Peru, and Bolivia consist at depths mostly of the sulphide of silver (and other metallic sulphides), which near the surface have been converted into native silver, silver-oxide, chloride, carbonate, etc., with much iron-oxide. This decomposed part of the lode, which often yields large quantities of native metals, is termed *colorades* from its red colour; while the black undecomposed sulphides at depths are called *negros*.

There is no known native sulphide of gold. The metal always occurs pure, or alloyed with silver and other metals,—in Transylvania with the rare metal tellurium. Nevertheless, there is evidently a close connection between the presence of pyrites and the occurrence of native gold. Auriferous quartz-veins frequently contain decomposed iron-pyrites, which gives the quartz a rusty appearance and a cavernous structure, while occasionally particles of gold are scattered through the mass. The undecomposed pyrites also sometimes contains gold, but in so fine a state that it cannot be extracted in the ordinary way, and can only be obtained by decomposition of the pyrites. The state in which it exists in this combination is little understood; but, as a sulphide of gold, which combines readily with other metallic sulphides and is soluble in alkaline sulphides, can be formed artificially, we can conceive the same to occur in ordinary course in the more powerful laboratory of nature. It is also possible that as silicic acid unites with many metals, it may combine with gold at the great heat and pressure under which the quartz-veins have been formed; and that this silicate, being an unstable compound, has parted with its gold as the quartz cooled and solidified. Gold is said also to exist, though in infinitely small quantity, in solution in some waters; and sea-water is said

to contain, not only an appreciable quantity of silver, but even traces of gold.

General Effects. While we cannot always imitate the processes which have taken place at great depths and under conditions impracticable with the means at our disposal, we know at all events the resultant minerals, although we may be ignorant of their genesis. Combinations, stable under their normal conditions, are often no longer so when brought within the oxidising influences of the external atmosphere, where they undergo changes which are within the reach of our experience and within the grasp of our means of research. We can thus see how from a few simple primary minerals, the great variety of secondary oxidised minerals have resulted—minerals slowly evolved during long processes of change, and taking, as they separate out, definite crystalline forms of great beauty and infinite variety.

There are also minerals which, under the influence of the surface-waters, have been dissolved and removed, and their place filled by other mineral matter brought down by the same waters which effect the destruction of the original minerals,— whence has resulted a variety of the curious pseudomorphs known to mineralogists.

Stratified Ore-deposits. These consist principally of iron-ores interstratified in various sedimentary strata. They occur both in nodules and in regular layers or beds of considerable extent in strata of every age. Manganese is also widely dispersed, but rarely in beds. As these minerals are derived by degradation either from pre-existing vein-lodes and aggregations, or from decomposed igneous rocks, they are very extensively distributed, both in a massive state and as the colouring matter of rocks and clays; they also occur in the surface and other waters. Owing to the same cause, other metals susceptible of forming soluble salts, especially sulphates, which by reduction pass into sulphides, are very widely dispersed, though in small quantities, through the sedimentary strata. Even the rarer and more insoluble metals are in this way present in minute quantities in many clays and mineral springs, and have also been detected in sea-waters [1].

It is singular, however, how rarely the native non-oxidisable metals are found incorporated in sedimentary strata, common as they are in recent detrital beds. With the exception, before mentioned, of gold grains or dust in the Molasse of Switzerland, in the Eocene rocks of Transylvania, and in a Carboniferous conglomerate of Nova Scotia, such derived secondary deposits are almost unknown. Very minute traces of gold are said to have been detected as thin films coating grains of pisolitic iron-ore in the Lower Tertiary strata of the neighbourhood of Epernay.

[1] According to Forchhammer ('Phil. Trans.' for 1865), there are present in sea-water, in addition to the commoner substances before named (p. 109), although often in almost imperceptible quantities,—fluorine, carbon, silicon, boron, aluminum, barium, strontium, lithium, silver, lead, copper, zinc, cobalt, nickel, arsenic, iron, manganese, gold, rubidium, cæsium.

The common iron-ores of the ordinary sedimentary strata occur in the state of red hematite,—of impure carbonate of iron or clay-ironstone,—of oolitic iron-oxides,—and of brown hematite and limonite.

Devonian and Carboniferous Orė-deposits. Red and brown hematites are found in Devonian and in Carboniferous strata, having originated either as aggregations or chemical precipitates. In the Coal-Measures iron occurs as a clay-ironstone, sometimes forming great tabular masses, at other times, large concretions, often septarian, with calcite, blende, pyrites, etc., in the fissures of shrinkage. Some of the bands are black, owing to the presence of carbonaceous matter (*black bands*). This form is much worked in the north of England and Scotland. But the more common form in this country is that of layers of small flattish nodules (with the same minerals as above) lying in the planes of lamination of many shales of the Coal-measures. It is these beds which are so largely worked in the coal-fields of the Midland Counties and Wales. The iron-stone nodules are concretions segregated from out of the mass of argillaceous sediment as it solidified into shale, round a shell, leaf, or other fossil, which are thus often admirably preserved.

The wide-spread occurrence of this clay-ironstone in the Coal-measures, not only of Europe but of America, is a very remarkable fact. It every-where forms a valuable ore extensively used. This species of ironstone generally contains small quantities not only of manganese, but also of titanium; and appreciable quantities of the latter metal have been detected in a number of the associated Coal-measure shales and clays. Now, manganese is a common and titanium a frequent ingredient in many volcanic rocks. The other constituents of the shales are earths and alkalies (*ante*, p. 27), such as would also result from the decomposition of these rocks (p. 41). It is highly probable, therefore, that much of the iron dispersed through the Coal-measures may, together with the other constituents of the argillaceous beds, have been derived, as the result of weathering and oxidisation, directly from the vast masses of volcanic rocks which burst out during the Silurian and early Carboniferous period; and that the subsequent large reduction and conversion of the iron to a carbonate of the protoxide was due to the presence and general diffusion of the remains of the luxuriant plant-growth of the Coal-measure period.

Permian Ore-deposits. In the succeeding Poikolitic series iron continues to be widely dispersed, but in a different state of oxidisation or of combination, and under conditions not favourable to its segregation and massing. Its universal dispersion as a colouring matter in rocks of Permian and Triassic age is, however, a very striking feature, and the sum total of iron, derived from the degradation of volcanic or other rocks, present in these strata must be very considerable.

But the important minerals of the Permian strata are the copper-ores.

These are due to the destruction of pre-existing copper-bearing lodes and segregations, and to the formation from these of extensive secondary cupriferous sedimentary beds. The western flanks of the Urals are bounded by Lower Permian strata, consisting of grits and sandstones derived from the waste of the rocks of the Urals and the country further eastward. The mineral-bearing beds, which are more than 100 feet thick, and thin out as they range westward, are said by Murchison to contain copper throughout. The ores are principally malachite, with red copper and copper-pyrites. Plant-remains are common, and in places there are thin subordinate beds of coal. Cupriferous concretions have generally formed around the carbonised stems of plants, and interlace with the fibres of the fossilised wood, so that these plant-beds have become a great storehouse of the copper-ores. Murchison was of opinion that the beds were not rendered cupriferous 'by the degradation of pre-existing copper-lodes and by the dissemination of their particles in the adjoining sea,' but by springs charged with salts of copper flowing into the Permian sea from the Ural chain, and 'then undergoing a peculiar change of composition[1].' But if the detrital matter itself of the Permian strata be derived from the lode-bearing rocks of the Urals, then the abraded copper-pyrites, which is not stable in presence of moisture and water, would be converted into the sulphate, and this salt, carried down by the surface waters, would then by reaction of the vegetable matter lead directly to the formation of the carbonates and copper-oxides found in the derived strata.

The copper-ores in the Lower Permian strata of the Riesengebirge, in Bohemia, present a close analogy with these of Russia. The sandstone abounds with the carbonised remains of plants, and the ores, which consist essentially of the green (malachite) and blue (azurite) carbonate of copper, and of the silicate of copper (chrysocolla), occur mostly in connection with coaly matter, and surrounding the carbonised trunks of trees. The bituminous shales underlying this bed are also rich in copper. The coarse conglomerates of Bomischbrod, which are of the same age, are penetrated by irregular layers of similar ores, which likewise locally form the cementing medium of the rock. Cotta considers these ores to be due to subsequent impregnations; but they seem to be more probably formed, like those at the base of the Urals, first by the oxidisation and then by the carbonisation of mineral matter derived from older lodes of copper-pyrites. Scarcely a trace of copper-pyrites is found in the reconstructed strata.

The bituminous copper-slate of the Hartz district is remarkable as well for its numerous fish- and plant-remains, as for its copper-ores. It forms a thin bed, which, although only one to two feet thick, has a very wide horizontal range at the base of the Zechstein. There is a singular ad-

[1] *Op. cit.* pp. 144, 168.

mixture of ores, which are either finely or invisibly distributed or else form thin layers and nests, consisting of copper- and iron-pyrites, or of oxides of copper with galena, silver, zinc, nickel, etc. An excess of animal and bituminous matter has here partly effected a further reduction back into sulphides.

A very illustrative instance of the changes caused by the decomposition of copper-pyrites occurs at Chessy near Lyons. The Bunter Sandstone there abuts against a highly inclined mass of gneissic, micaceous, and talcose schists. The old rocks are traversed by masses or dykes of aphanite (diorite, var.), with which are associated segregations of copper- and iron-pyrites, and blende, forming large lenticular layers (*a*, Fig. 187), parallel to the foliation of the rock. The outer portion of the aphanite is decomposed into a whitish-grey rock, and the yellow pyrites, which it contains, is transformed into grey and black oxides. At the weathered junction with the Triassic rocks there is a stratum, 6 to 12 feet thick, of red clay (*d*) containing angular fragments of quartz and aphanite, and impregnated with the red oxide of copper. In the beds of the Bunter sandstone succeeding this clay is found a fine variety of azurite, with some malachite, in geodes (*e*), that extend about 60 feet into the sandstone, in which there is also much diffused peroxide of iron.

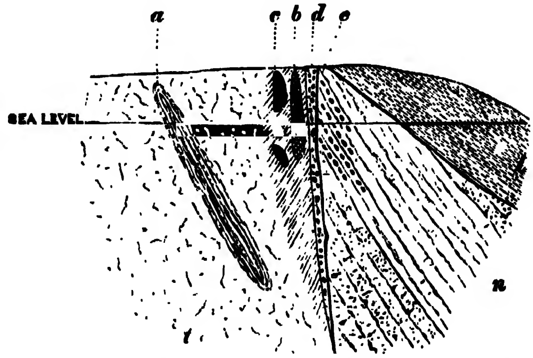

FIG. 187. *Section of the Copper Mine at Chessy near Lyons.* (Cotta.) *l* Lias. *n.* New Red Sandstone. *t.* Crystalline Schists with dykes of Aphanite (*a*). Depth about 700 feet.

We have here, therefore, at *a*, the ore in its normal state of copper-pyrites; at *b* it is partly decomposed *in situ*; in *c* it is re-formed, altered and converted into the red oxide of copper; and at *d* into the blue and green carbonates; while at *e* the copper has been precipitated or crystallised as a pure blue carbonate, and the iron has separated out and dispersed in the surrounding strata in the state of the peroxide.

In Silesia, Triassic clays (Keuper) contain layers and scattered large nodules of a grey clay-ironstone, consisting partly of spherosiderite, and partly of argillaceous limonite. The nodules are generally honey-combed, and contain crystals of spathic iron, blende, and galena, with, occasionally, casts of Ammonites.

Jurassic Ore-deposits. A thick local bed of iron-ore occurs in the upper part of the Lower Lias of Lincolnshire; but the great deposit of Liassic iron is in the Middle Lias or Marlstone. It forms, in the Cleveland district, thick and important beds of a greenish-grey fossiliferous rock

composed essentially of the carbonate, with variable proportions of the silicate of the protoxide of iron, which decomposes at the exposed surfaces into a brown oxide. A similar bed, about 12 feet thick, is worked at Fawler, Adderbury, and Steeple-Aston in Oxfordshire.

The sandy beds at the base of the Inferior Oolite are often ferruginous, and form in Northamptonshire and Lincolnshire important and largely worked beds of impure brown hematite. The Oolites of Yorkshire are also rich in great concretionary masses and nodular bands of ironstone. The earthy brown hematite of Westbury, Wilts, belongs to the Coralline Oolite.

The Jurassic strata of the South of France contain, in the Ardèche, some valuable beds of red and brown hematites, sometimes compact, at others with a loose oolitic structure. Throughout the whole of Bavaria and Wurtemberg, the Brown-Jura series contain subordinate beds of ironstone, consisting of compact brown hematite, or of limonite in oolitic grains. Of the same age and character are the important deposits of iron-ore in the Luxembourg and in adjacent parts of France.

Neocomian and Cretaceous Ore-deposits. The lower division of the Wealden series contains some beds of clay, intercalated with sandstones, in which there are nodules of a clay-ironstone, formerly largely worked at Ashburnham and other places in Sussex. At Shotover, near Oxford, there are thin beds of a compact sandy dark-brown hematite, with a few bands of freshwater shells, that have been occasionally worked as a poor iron-ore. The same series contain also yellow and ochreous earthy limonite, wrought for ochre. In the Boulonnais, a bed (5 to 10 feet thick) of a rubbly brown limonite, apparently of freshwater origin and of Wealden age, caps the Jurassic hills around St. Etienne, south of Boulogne. At the base of the Middle Neocomian, or Lower Greensand of Seend, near Devizes, there is a bed, 15 to 20 feet thick, of a soft ochreous sandy brown hematite; and a more concretionary variety occurs in large nodules in the sands of Buckinghamshire. The Tealby series of Lincolnshire contains a thin workable bed of iron-ore, oolitic in structure. Similar beds of the same age are worked near Vassy in the Haute Marne and in Hanover.

It is possible that the brown hematites of Westbury, Seend, and some others were originally green silicates and carbonates of iron which have been altered by weathering in a manner analogous to that which has produced such remarkable results in the lode-ores. Near Adderbury, though the rock is compact, it exists in both the unaltered and altered state.

Tertiary Ore-deposits. The Chalk in the neighbourhood of Brighton is traversed by a few fissures and pipes filled with a sandy brown hematite, probably of early Tertiary age[1]; and at the base of the Barton series on the coast near Christchurch are some large ferruginous septaria,

[1] The Lenham Ironsands overlying the Chalk above Folkestone and Lenham seem, at some early period, to have been used for smelting.

that were once employed with other ores. Neither are of any importance. In the Jurassic limestones of the Department of the Lot, there are numerous fissures filled with brown clay and ochreous iron-ore, with concretions of limonite, considered to be of Tertiary age, and an oolitic variety is also worked in Perigord, Franche-Comte, and other parts of the south of France.

Recent Ore-deposits. Iron deposits are at present in course of formation at the bottom of many morasses and lakes; but it is only occasionally that the quantity is sufficiently large to be worked. In the low lands of North Germany, Scandinavia, Canada, and elsewhere, a granular and concretionary form of limonite is dredged from the bottom of lakes, where it accumulates to the thickness of a few inches to three feet, and is being constantly elaborated from the surface waters, apparently by the agency of diatoms. The iron is in all probability originally supplied to these waters by the decomposition of iron-pyrites and ferruginous silicates in the neighbouring rocks. It is thought that some of the older limonites may be due to agencies of a like description.

Ore-bearing Drift-deposits. These are confined to the native metals and a few indestructible ores. Their origin is simple. By the degradation of surface rocks traversed by metallic lodes, and by the action of the powerful rivers of Quaternary times, old valleys have had their channels partly filled up with the more or less rounded and worn fragments of the adjacent rocks and lodes; and these fragments in their successive transport by floods and freshets have become roughly sorted, the heavier materials gradually working downwards, so that the metallic portions are found chiefly at or near the base of the detrital matter.

In this way the tin-lodes of Cornwall have furnished the fragments of cassiterite, formerly so largely worked in the valley-gravels of that county; but, like the gold *placers* of other countries, they are of limited extent, and after a time cease to give profitable returns. These tin-drifts have been wrought from a remote period, and few that are unworked now remain. They occupy the bottom and flanks of the valleys, which were deeper then than now, and often extend below low-water-mark. The following account is abridged from Henwood's section of the Perran well stream-works [1].

1. Angular gravel and sand, with rounded masses of granite and slate of local origin, in unequal beds; horn of deer and oysters at base	12 to 15 feet.
2. Fine silt with oyster shells, leaves, nuts, etc.	½ to 1½ „
3. Tin ground, consisting of angular and sub-angular blocks of the schorl-rock, granites, quartzose slates, etc., of the district, with more or less rounded fragments of tin-ore; and resting on the rocky bottom	2 to 3 „

In a valley opening into the estuary of the Par near St. Austell, the surface of which is little above the sea-level, the tin ground, which was 5 to 6

[1] 'On the Detrital Tin Ore of Cornwall,' Journ. Roy. Inst. Cornwall, No. xv.

feet thick, was overlain by beds of gravel, sea-sand, clay, and peat, from 40 to 44 feet thick.

No fossils are mentioned as occurring in the lower or tin-bed; but from other circumstances there is reason to suppose that most of these tin drifts are of Quaternary age. These detrital beds contain also microscopic particles of gold, derived from the lodes of copper- and iron-pyrites.

The quartz-lodes of Wales, Sutherlandshire, Berwickshire, Wicklow, and other parts of Ireland, have given rise to more valuable auriferous gravels. In parts of Wales pebbles of galena are found in the river-gravels.

But these deposits sink into insignificance in comparison with the thick masses of auriferous drift accumulated in some of the valleys of Russia, Australia, and California. Murchison states that the first are confined to the eastern slopes of the Urals, and present two forms of deposit:—one, which occupies the bottom of the plains and is covered by alluvial clay, is referred by him to lacustrine origin; and he gives, as an instance of this, the section of the valley of the Berezof near Ekaterinburg where the gold-drift is from 10 to 15 feet thick. It seems to me, however, to be a true old river-valley gravel.

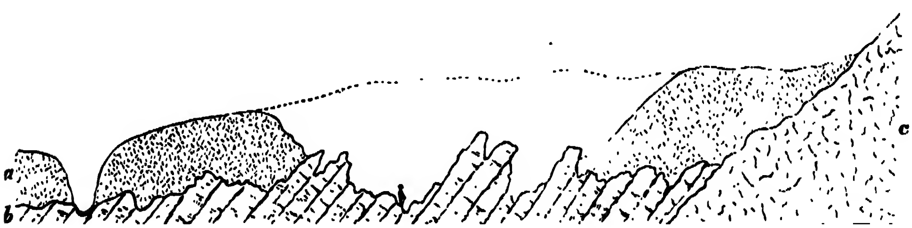

FIG. 188. *Section of the Auriferous Drift at Soimanofsk, near Miask, in the South Ural.* (Murchison.) *a.* Angular drift. *b.* Limestone. *c.* Eruptive and Serpentine Rocks.

The other is a local detritus of angular fragments of the adjacent rocks, often partly filling the narrow transverse valleys, where it is piled up in accumulations attaining to the thickness of 50 feet and more. Generally there are no mammalian remains in this angular drift, though remains of the elk have been found in an overlying clay; but near Miask, Fig. 188, remains of the mammoth were found about 50 feet beneath the surface of this gravel, which there lies on a singularly eroded surface of limestone rocks.

The auriferous drift-deposits of Australia consist of gravels, sands, and clays, without any regular order of superposition. At the base there are often large quartz boulders, 4 to 5 cubic feet or more in volume, and it is in the basement *wash-dirt* (*g*, Fig. 189) especially that the gold is abundant. Unctuous brown, buff-coloured, and whitish clays, derived from the decomposition of adjacent felspathic rocks, are of frequent occurrence. Bones of large mammalia occur occasionally, generally near the base. Eruptions of basalt took place during the accumulation of the drift, and while portions of it are free from basaltic débris, other parts are covered by basalt, and

boulders of the same are common in the gravels of later date. The thickness of some of these old valley-deposits is remarkable; shafts, which have made the Australian geologists[1] intimately acquainted with the structure of these drift-deposits, having in places been sunk to the depth of several hundred feet.

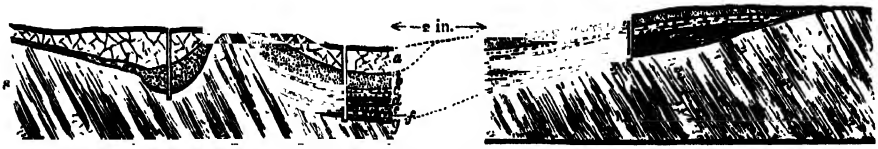

FIG. 189. *Section of Auriferous Drift at Ballarat, Australia.* (Brough Smyth.)
a. Basalt. *b.* Yellow Clay *c.* Sand and Gravel. *d.* Red Clay. *e.* Sandy drift. *f.* Black Clay *g.* Wash-dirt (gravelly clay). *s.* Palæozoic schists. Horizontal scale: 1 inch = 1000 feet. Vertical scale: 1 inch = 500 feet.

In California, detrital gold is found in an old drift of Quaternary age capping the hills and also in the reconstructed alluvial beds of the valleys. At the base of the western flanks of the Sierra, loose sand and gravel with boulders cover extensive plains; but in proceeding further inland, the older detrital beds attain to very high levels, sometimes rising to the height of 2000 feet above the level of the adjacent stream, with a thickness of from 200 to 600 feet. The upper portion of this deposit, which is in places covered by sheets of basalt[2], consists of a reddish loam mixed with small gravel, below which is a coarse gravel with large boulders chiefly of quartz. This bed is very auriferous, the gold being scattered through the gravel, though it mainly occurs in the portion immediately above the rock on which the 'drift' rests. The younger gravels in the ravines descending from the central ridges are likewise often rich in gold.

The many relations this subject of mineral veins has with metamorphism,—with questions of subterranean temperature,—the distribution of the elements at depths,—and the physical effects of the disturbances of the earth's crust,—renders it one of very considerable importance to the student.

[1] 'The Gold Fields of Australia,' p. 172.

[2] It is supposed that the direction of the flow of the basalt was governed by the position of the old valleys. The intervening higher ground (probably not similarly protected) has since been removed by denudation, which has reached to the depth of the present valleys, while portions of the beds of the former valleys, in the form of old river-gravels, are said to remain on the basalt-capped hills on either side.

CHAPTER XX.

IGNEOUS ROCKS.

DIVISION OF THE IGNEOUS ROCKS. THEIR CLASSIFICATION. VOLCANIC ROCKS. VOLCANOES OF PAST PERIODS. THE EXTINCT VOLCANOES OF TERTIARY AGE: AUVERGNE; THE EIFEL; CATALONIA; ITALY; GERMANY; THE CAUCASUS; ASIA; AUSTRALASIA; OCEAN ISLANDS; THE RED SEA; NORTH AMERICA. DIVISION OF THE CALIFORNIAN VOLCANIC ROCKS. VOLCANOES OF OLDER DATE: INDIA; BRITISH ISLES; MULL. JURASSIC AND PERMIAN ERUPTIONS. CARBONIFEROUS ERUPTIONS: DERBYSHIRE. BASIN OF THE FRITH OF FORTH. DEVONIAN ERUPTIONS: SCOTLAND. SILURIAN ERUPTIONS: WALES; CUMBERLAND; IRELAND. CAMBRIAN ERUPTIONS: WALES. PRE-CAMBRIAN ERUPTIONS: PEMBROKESHIRE.

Division of the Igneous Rocks. The term igneous rocks has been commonly applied to those which are regarded as having been once in a molten state,—whether from igneous or hydro-thermal fusion,—and either have been erupted through the overlying sedimentary strata, or injected into them, without necessarily reaching the surface. Although the chemical analysis of these rocks, each in their respective classes, closely corresponds, yet, owing to the very different conditions under which they have been consolidated, they present great differences in mineral structure and composition, and in appearance. This has led to their being grouped into two divisions, namely, *volcanic* rocks and *plutonic* rocks; and these again are subdivided into various sections, according to the character, condition, and proportion of their constituent minerals, of which the principal have been described in Chapter III. We now have to look at these rocks in their geological bearings.

Their Classification. The foregoing division of the igneous rocks, although in many respects convenient, is not strictly correct in the sense in which it was originally used, which was, that they constitute distinct groups of rocks, not only formed under different conditions, but possessing special and distinct characters. As now understood, it, in many cases, indicates a difference of conditions rather than of origin. The volcanic rocks having been erupted on the surface, and having cooled quickly and without pressure, have solidified as non-crystalline and amorphous rocks, whereas the so-called plutonic rocks not having been erupted at the surface, and cooling slowly and under great pressure, have solidified as crystalline rocks—lava and basalt representing the extremes of one series, and granite and syenite

the extremes of the other. It is now contended that there are cases in which the non-crystalline volcanic rocks pass downwards into the crystalline so-called plutonic rocks, or in which the latter pass upwards into amorphous and non-crystalline masses; and that, so far as lithological composition is concerned, little or no distinction exists between them. Nevertheless it would be inconvenient to abandon the term *plutonic* to indicate those rocks which, from their distinct mineral structure, have clearly been consolidated under heat and pressure, although the term is open to the objection that it includes rocks whose crystalline structure is now considered to be due to an extreme term of metamorphism. It must therefore be understood to indicate only certain physical and mineral conditions, and not to have reference to the initial origin.

A nomenclature, dependent more on the chemical and petrological relations of the various rocks, such as is implied by the use of the terms *acidic* and *basic*, which groups together the rocks derived from the same magma, is, provided it recognises the difference of structure produced by the different conditions of vulcanism and plutonism, in some cases better adapted for geological purposes.

We may therefore take the 'igneous' rocks to include all the 'volcanic' rocks of whatsoever mode of eruption, together with one section of the so-called 'plutonic' rocks: another section will be treated of further on under the term of 'pseudo-igneous' rocks.

Volcanic Rocks. The phenomena of the modern volcano and its products have already been described. Let us now enquire how far similar phenomena and similar products are to be recognised in past geological times. They were at one time supposed to be essentially different, but recent researches have proved that there is at all events an intimate relation between the volcanic rocks of the present day and those of all the geological periods. But although these researches have shown that sub-aerial and explosive volcanic action existed in the earliest times, and that the erupted rocks of all dates are very similar in composition, they fail, I think, to show, so far as the much effaced evidence enables us to judge, that the earlier volcanic mountain was of the same importance as the modern volcano, or that the eruptive phenomena were of the same character. Not that there was less volcanic activity, but it was exhibited in a different form.

This will be best understood by comparing the volcanic phenomena of the successive geological periods, commencing with the well-preserved recent volcano to the dimmer forms of earlier times. We may thus be enabled, after making all due allowance for the changes and degradation which the earlier structures have undergone, to judge of the relative numbers and importance of the crater-volcano in past times. I shall not however adopt the usual plan of speaking of all the volcanic rocks of whatsoever age as

'lavas,' because this might imply crater-eruptions from a central vent. It is to the latter, so far as they can be distinguished, that I propose to restrict the term 'lava;' whereas to the other important group of volcanic rocks, which are the products of the fissure eruptions, the old term 'trap' should, I would suggest, be confined[1]. The reasons for this will be made more apparent in the sequel. In the meantime, in speaking of volcanic rocks generally, it will be understood that I include both the one and the other group.

Volcanoes of Past Periods. The absence of well-defined volcanic cones, and apparently of the more common modern volcanic materials amongst the rocks of Palæozoic and Mesozoic age, led many geologists at one time to suppose that true volcanoes did not exist before the Tertiary period. But the enormous denudation which the older, and even many Tertiary, formations have undergone has so obliterated the original surface features, that only perhaps in a few exceptional cases could we expect such prominent and generally unconsolidated objects as volcanic cones to have escaped destruction, or at least such change as to render them almost unrecognisable. Or, if ancient volcanoes with their masses of loose ashes, scoriæ, and lava-streams have existed, it is supposed that, when they have been covered up under subsequent accumulations of sedimentary strata, these various volcanic products have undergone so complete a change, by processes of infiltration, alteration, and cementation, as to lose altogether their original character, and to present now,—in place of loose and scoriaceous materials,—compact tufas, solid agglomerates, ash-slates, and other changed forms of rock.

The Extinct Volcanoes of Tertiary Age[2]. The extinct volcanoes of geological times link on to the modern volcano by many survivals from the later of those times. The eruptions of some of the most important existing volcanoes have commenced in various Tertiary periods; Etna dates back to Pliocene times, Vesuvius to Pleistocene times[3], and Hecla also to late Tertiary times. Their age is generally well marked from the circumstance that the earlier eruptions were often submarine, so that the ejected volcanic matter became interstratified with marine strata of the several epochs. Other Tertiary volcanoes became extinct at different periods before our times; and in almost all cases, these can be shown, like the modern volcano, to have had a prolonged existence. But it will be found that, as we recede in time, the distinctive form and features of the

[1] In describing, however, the work of other geologists, such as the local descriptions by Dr. Archibald Geikie and Prof. Judd, of presumed old volcanoes of Scotland, I have adhered to the terms employed by the respective authors.

[2] For full particulars of recent and extinct volcanoes and their products, the reader should consult Daubeny's 'Volcanos,' 2nd edit., 1862; Scrope's 'Description of Volcanos,' 2nd edit., 1858; Judd's 'Volcanoes,' and other works referred to in the following pages.

[3] See a paper by Dr. Johnston-Lavis in the 'Quart. Journ. Geol. Soc.,' February, 1884.

volcanic mountain become, owing to the causes above referred to, more and more obscure, until at last it is with difficulty that their identity and origin can be established. The distribution of the active, as well as of the more recently extinct volcanoes, will be found on Map No. II, p. 216.

Auvergne[1]. Amongst the most striking and instructive of those extinct volcanoes are those of Auvergne. They form three separate groups, extending over the high granitic platform of Central France, for a distance of about 100 miles from north to south, with a width of from 20 to 80 miles. The eruptions commenced in Miocene times, and continued without interruption to Pleistocene or pre-historic times. It is a most striking sight to see the small cones or 'Puys' of the later date, of which there are not fewer than 230, still looking as fresh and perfect as though they had been in eruption within the present century. Many of the craters are entire, except at the side where a lava-stream has issued, and the lava-streams themselves, which may be traced for distances of from 1 to 12 miles, are still as bare, rough, and barren as those of Etna and Vesuvius. The comparatively recent age of some of these streams is, however, clearly indicated by the fact that where they have found their way to the lower levels, they often cover up old valley-gravels containing the remains of extinct Pleistocene mammalia and mollusca. In the Ardèche the streams have filled valleys to the depth of 150 feet, with a width of half-a-mile; and where worn through by the present rivers, the lava is seen to be as compact as the older basalts of the plateaux, and in many instances shows, like it, beautiful columnar structure.

FIG. 190. *The Breached Volcanic Cones of the Puys Noir, Solas, and La Vache, Auvergne.* (Scrope.)

These newer cones (puys) are often apparently on lines of fissure, along which, as with those of Etna, they have broken out in succession and in near proximity one to another. They are sometimes placed directly on the granitic platform, and at others on the basaltic plateaux formed by older eruptions.

These great basaltic plateaux, accompanied by thick accumulations of volcanic tufa, commence with alternations of lacustrine deposits of Pliocene age. Scrope remarks that only in a few cases can those vast sheets of basalt be connected with volcanic cones, and these are generally reduced to

[1] See Scrope's 'Geology and Extinct Volcanoes of Central France,' 2nd edit., 1858, and Lecoq's 'Les Époques géologiques de l'Auvergne,' 1867, and map.

scoriæ heaps or to mere stumps. Many geologists, including M. Lecoq, who resided for years in the district, are, however, of opinion, that the basaltic plateaux in general are due, not to crater eruptions, but to outwellings from fissure eruptions, the lines of some of which are still marked by more prominent basaltic bosses or peaks.

Where these great masses of basalt are cut through by the existing valleys, they often exhibit magnificent rows of columnar prisms, separated by beds of scoriæ and agglomerates. Of these, Mr. Scrope and M. Lecoq give some admirable illustrations. That the eruptions were prolonged through a long geological period is evident from the many different levels of the plateaux, and from the fact that beds of basalt are interstratified with some of the older trachytes, while they were continued up to the time of the *Puys* of Pleistocene date.

But there were eruptions of an earlier date, which were more centered, and took place from the three great extinct volcanoes of Mount Dore, the Cantal (Fig. 77, p. 194), and Mont Mezen. These mountains, although they rise to heights of 5000 to 6000 feet or more, retain, as a consequence of their greater antiquity, but little of the aspect of volcanoes. No regular craters can now be traced, but the district is covered with beds of scoriæ and pumice, interstratified with streams of trachytic lavas, which are exposed by the deep valleys with which the mountains have become scored. It was essentially, but not wholly, a period of trachytic ejection, to which succeeded great floods of basalt[1]. At a subsequent period, only anterior to the latest of the Puys of the district, there was a recurrence on a smaller scale, and modified in its character (domite), of trachytic ejections,—not, however, in the old centres, but in the more northern Clermont district.

The Eifel. This is another district of great interest, in which the volcanic action likewise dates back to Miocene and ends in Pleistocene times. The cones of the later period, of which there are about forty, are, like those of Auvergne, remarkable for their excellent state of preservation. The strata burst through consist of Devonian rocks, ejected fragments of which, together with some fragments of crystalline schists and of granite, constitute in many cases a large proportion of the débris forming the cones. The other peculiar features of this region are the number of crater-lakes, the large amount of scoriæ, lapilli, and ashes, and the paucity of lava-currents, all indicating the explosive character of the eruptions. The Loess of the Rhine has extended over some of these extinct craters.

Catalonia. A well-preserved group of fourteen volcanic cones exists near Olot,—a town near the foot of the Pyrenees in the north-east of Spain. These cones are situated on nummulitic strata of Eocene age. Some of

[1] Captain Dutton thinks that the rocks of this locality, called basalt by Scrope, may prove to be augitic andesite (the augite-trachyte of Zirkel).

them seem to have been of very recent geological date, the cones being very fresh-looking and the lava-streams having taken the course of the existing valleys, where they overlie the valley-gravels. In places the lava has been cut through to the depth of 50 to 100 feet by the present rivers.

Italy. In Central Italy and the chain of the Apennines there are many old volcanic hills, while in the Euganean hills of Northern Italy we find all the phenomena presented by a great ruined volcano. The Campagna of Rome is an old volcanic district formed of peperino and tuff; and the beautiful crater-lakes of Albano, Nemi, and others, mark the sites of old explosive vents.

In **Sardinia** there is a fine group of extinct volcanoes in the Tertiary district of the north-west of the island.

FIG. 191. *The Kammerbühl, an old volcanic hill, as seen from the south-west.* (Judd.)

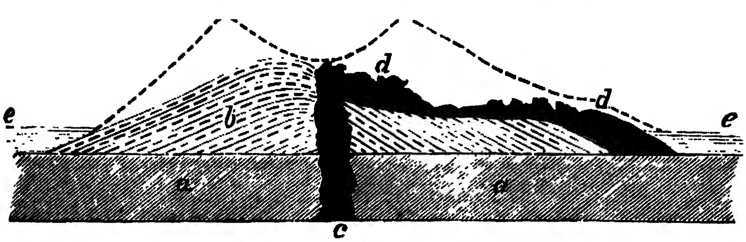

FIG. 192. *Section of the above, showing the probable former outline of the Volcano.* (Judd.)
a. Metamorphic rocks. *b*. Basaltic scoriæ. *c*. Plug of basalt rising through the centre of the pile. *d*. Lava-stream composed of the same lava. *e*. Alluvial beds.
(The dotted line indicates the probable former outline of the volcano.)

Germany. The small isolated hill of Kammerbühl, near Eger, in Bohemia, consists of regular layers of basaltic scoriæ, with numerous angular fragments of schistose rocks and quartzite, often exhibiting a burnt appearance, and with a few volcanic *bombs*. A solid mass of basalt rises through

the centre of the hill, while the remains of a lava-stream can be traced from the summit down part of its western slope. As the loose scoriæ are largely worked for road-stone, clear sections are exposed, in which these materials exhibit a remarkably fresh appearance, notwithstanding that the hill has lost the distinctive features of a volcano, and the date of eruption seems obscure [1].

Professor Judd states that all through northern and in part of western Bavaria, as also of Silesia and Central Germany, isolated hills of basalt, like that occupying the centre of the Kammerbühl, occur by hundreds. These he thinks may be old volcanic centres, bared of their cinder-cones by denudation.

The interesting volcanic district of Schemnitz in Hungary, which covers an area about 50 miles in diameter, is regarded by Judd as the basal wreck of a grand volcano of Miocene age, consisting of a vast central mountain, on the sides of which, as on Etna at the present day, innumerable parasitic cones poured forth their lava-streams. These lavas are trachytes or andesites, the deeper portions of which, exposed by excessive denudation, pass, in his opinion, into greenstone-trachyte, syenite, and even granite [2].

In the **Caucasus** there are several large extinct volcanoes with lava-streams of andesite. Some of these seem to have been in eruption at a comparatively recent period.

In **Asia Minor** there exists a remarkable group of some thirty extinct volcanoes in a district extending for some distance inland from the gulf of Smyrna. The mountain of the Little Ararat is an extinct volcano, while the Great Ararat has been in eruption within historical times. The older volcanoes of the Taurus chain emitted trachytic lavas.

In **Central Asia** there is a well-marked group of extinct volcanoes in the district of Mandchourie and Turans.

In **Australia** there are some well-preserved cones of extinct volcanoes in the colony of Victoria; and in Auckland, New Zealand, they are still more numerous.

Ocean Islands. Madeira is a volcanic island of Miocene and Pliocene date. St. Helena and Ascension may be older. The Azores, Cape Verde and Canary Islands are likewise of volcanic origin.

In the Southern and Indian oceans are the extinct volcanoes of St. Paul, the Crozet Islands, Kerguelen, and others.

The Red Sea. Aden is the centre of an old volcanic district; and the town is built on a depression referred by some to an old crater. Perim is an old volcano into the crater of which the sea now enters.

On both shores of the Red Sea there are, with a few volcanoes now

[1] Judd's 'Volcanoes,' p. 113, 1883.

[2] 'Quart. Journ. Geol. Soc.,' vol. xxxii. p. 292, 1876.

active, many others which are extinct. In Sinai and the district to the south there are also a number of old extinct craters.

North America. In the New World volcanic phenomena are exhibited on a scale of extraordinary grandeur; and, while the volcanic activity is not yet extinct, the eruptions date back to yet earlier geological periods than in Auvergne. A wonderful series of volcanic rocks extends, on the Pacific side, from New Mexico and North California to Oregon and British Columbia—a distance of about 800 miles, with a width of from 80 to 200 miles,—spreading over an area estimated at not less than 150,000 square miles. The whole of this vast area is covered with massive sheets of basaltic and trachytic rocks, except where mountain-ridges rise through the plateaux, or where the rivers have excavated long and deep valleys through to the sedimentary substrata or to the granitic base. Vast plateaux of volcanic rocks rise gradually from heights of 4000 to 5000 feet in the northern parts, to 8000 to 10,000 feet in California and New Mexico, and attain at the summit-level in Colorado a height of 14,000 feet. They form great flat dome-shaped masses, having the aspect, from their great extent, of almost level table-lands. In Oregon the sheet of basalt is at least 2000 feet thick; where cut through by the Columbia River, it is not less than 2000 to 3000 feet; while in other places these great masses of igneous rocks are estimated to have a thickness of as much as 7000 feet. The Snake and Columbia rivers flow through high basaltic walls for a distance of probably not much less than—the one of 100 and the other 200 miles.

The American geologists[1] ascribe the greater part of these outflows to fissure- and not to crater-eruptions. The earlier outpourings, largely developed in the central districts, commenced in Eocene, if not in late Cretaceous, times. Then followed outflows in the Miocene period; while the more widely extended succeeding basaltic outflows commenced in Pliocene, and were prolonged to late Pleistocene times. The great plateaux of the Cascade Range, cut through by the Columbia River and its tributaries, are many of them underlain by the Northern Boulder-drift. Clarence King estimates that in the districts he investigated basalt forms eight-tenths of the volcanic rocks.

It is not, however, to be concluded that fissure-eruptions alone took place. There were crater-eruptions from time to time throughout this lengthened period; but it was especially towards its close that they became more numerous, breaking through the capping of basalt and older rocks, and

[1] See Hayden, 'Reports of the U. S. Geological Survey of Colorado and adjacent districts,' from 1871 to 1880, and 'Bulletins U. S. Geol. and Geogr. Survey for 1876,' p. 208: Clarence King, 'Geology of the Fortieth Parallel,' vol. i. pp. 579, 615, 632, 655, 672: Le Conte, 'Amer. Journ. Science and Art,' 3rd ser., vol. iv. 1872, pp. 460, 470: J. W. Powell, 'Exploration of the Colorado River,' 1875: Capt. Dutton, 'Geology of the High Plateaux of Utah,' 1880, etc.

forming small ash and scoriæ cones, scattered in places over the surface of the plateaux. Still they constitute apparently features of very subordinate dimensions to the massive outwellings of molten rocks which flowed without explosive action through the great fissures, many miles in length, with which the area is intersected.

On the outskirts of this grand volcanic district there are yet mountains showing signs of volcanic activity, also lavas with scoriæ and cinders. Hayden[1] remarks of the Colorado district, that although the great basaltic eruptions have been productive of forms resembling crater-cones, not one has been observed that could directly be compared to the cone and crater of an active or typical volcano. Nevertheless the basalt often rises to high peaks representing former points of outflow; but this arises when there has been successive flows, during the intervals between which the basalt became rigid near the point of ejection, and thus gradually built up a mountain mass. There are, however, on the summit of these high plateaux remnants, as in Auvergne, of groups of true volcanic cones, though in many cases weather-beaten and nearly worn away. Dykes of basalt, extending in straight lines for many miles, run parallel with one another, and through these the great floods of molten rock have poured. A marked feature in connection with most of these dykes is the fact that no disturbance of the strata seems to have accompanied the ejection of the volcanic material. No distortion nor extensive displacement of the Cretaceous and Tertiary beds which they traverse has been noticed.

In Western Colorado Professor Powell observes that the later volcanic eruptions—those which welled out on lines of fault, some of which crossed the Grand Cañon—have left occasional heaps of scoriæ and cinders, one of which stands on the very brink of the cañon.

In another portion (Utah) of this grand volcanic district, Captain Dutton describes the eruptions as going back to the Middle Eocene; while the latest cannot be older than the Christian era[2]. There were many successive eruptions, but with long intervals. The older outbreaks of propylites and tufas have suffered such extensive denudation, or have been so completely buried beneath the later rocks, that little can be determined of their ancient topography. Then followed great outbreaks of hornblendic andesite in massive sheets spreading over large areas, and piling up mountain-masses. The topography of the succeeding and greatest period of activity—that of the trachytes—becomes somewhat more defined. Several foci of eruption are discernible, but no 'lofty Etna-like summits or craters are visible; and it is doubtful whether the method of eruption was generally such as would generate mountains of that character; for the larger deluges appear to

[1] Reports of 1876 and 1878.

[2] 'Geology of the High Plateaux of Utah,' 1880, p. 55.

have emanated from fissures located within restricted areas. Yet, apparently, some piles of important magnitude were reared by the successive superposition of *coulées* around a central vent or pipe, and still bear evidences of their origin, though they have been reduced to mere remnants by the wear of ages.'

The succeeding rhyolitic eruptions were also massive and have built up lofty mountains with broad tabular summits. The eruptions of basalt—the youngest of the eruptive rocks—were in this area on a smaller scale than those of the older volcanic rocks. There are large fields of basalt with cones of later date standing generally in a very dilapidated condition and nearly faded away; yet in some places the cones and streams are singularly fresh and perfect. Many of the cones are perched upon the brinks of terraced cliffs or cañon walls; and in a great majority of cases the vents stand near faults, and on the upthrow and not on the downthrow side. The larger floods, however, of this, as of the other igneous rocks, are supposed to have emanated from fissures within a restricted area.

In speaking of the Sevier plateaux, Captain Dutton remarks that all these lavas seem to have welled up in mighty floods without any of that explosive violence which often characterises volcanic action; the extravasated matter spreading out in wide fields, deluging the surrounding country like the tide in a bay, and flowing over all inequalities. There is here also, in the older of these floods, evidence of the existence of ancient volcanic cones buried in the seas of lava poured out around. A large tufa cone, which must once have been nearly 1800 feet high, and formed by showers of small fragments blown from the orifice, has been cut through, and a section of it has been exposed by the erosion of one of the deep valleys of the district. The fragments are sharp and angular, but the entire mass is consolidated into a coherent body of stratiform layers, dipping at an angle of 28° to 30° near the summit, and decreasing towards the base.

These great volcanic outflows, which succeed one another with admirable regularity in Western North-America, afford peculiarly favourable opportunities for investigating the contested question—whether or not there is a definite order of succession in the eruption of the igneous rocks. A certain order of succession has in fact been provisionally established; and this order is even considered by some geologists to hold good, both for Europe and other parts of the world, but on this point opinions are very divided.

Divisions of the Californian Volcanic Rocks. Richthofen divides the volcanic rocks of California and Nevada into five orders or groups, each more or less independent and of distinct geological age, while the different species of which the several groups or orders consist are connected by petrological characters, chemical composition, texture, and

specific gravity, and of these he gives full particulars in his elaborate paper[1]. Briefly, the great groups are as follows in order of antiquity, taken in descending succession[2]:—

		Approximate Age.
v. Basalt	... ...	*Pliocene, Pleistocene,* and *Recent.*
iv. Rhyolite	... ...	*Pliocene* and *Pleistocene.*
iii. Trachyte	... ...	*Miocene* and *Pliocene.*
ii. Andesite i. Propylite	... ...	*Eocene* and *Miocene.*

This range in time of the geological eruptions cannot be very precisely defined; the above determinations are merely approximate and relative. The petrographical classification follows a different order. Taken with reference to the proportion of silica, or from the more acidic to the more basic, Richthofen groups them as under in descending order:—

Orders.		*Families.*
5. Rhyolite (iv)	...	Lithoidic or hyaline (Rhyolite proper). Porphyritic Rhyolite (Liparite). Granitic Rhyolite (Nevadite).
4. Trachyte (iii)	...	Sanidine Trachyte. Oligoclase Trachyte.
3. Propylite (i)[3]	...	Quartzose Propylite. Hornblendic Propylite. Augitic Propylite.
2. Andesite (ii)	...	Hornblendic Andesite. Augitic Andesite.
1. Basalt (v) ...	...	Dolerite. Basalt. Leucitophyre.

Zirkel has introduced a few modifications in the above grouping. Thus he considers that the rhyolite group should be divided into,—*a.* Glassy rhyolite—obsidian, etc.; *b.* Proper rhyolite—the felsitic and porphyritic; *c.* Nevadite—or granitic rhyolite; that the oligoclase-trachyte should be transferred to the hornblende-andesites; and that a new division, under the name of augite-trachyte, should be introduced in its place. To andesite-trachytes (hornblende-andesites) with quartz he would restrict the term dacite, which, together with andesites and greenstone-trachytes with quartz, he would group with the propylites under the term of quartz-propylite.

Under the head of true basalts Zirkel places felspar-basalts, anamesites, and dolerites, these three varieties differing only in point of structure—the same principal constituents being common to all.

Volcanoes of older date. As we follow the volcanic eruptions further back in geological time, their topography becomes more and more

[1] 'The Natural System of Volcanic Rocks;' Mem. Californian Acad. Sciences, vol. i, 1868: and F. Zirkel's 'Microscopical Petrography,' U. S. Geol. Exploration of the Fortieth Parallel, vol. vi.

[2] For geological reasons I place them in reverse order to Richthofen.

[3] Propylite, according to some petrologists, is not a distinct species.

indistinct, and their centres of action more and more difficult to determine. Where cones and craters have existed, subaerial degradation and aqueous denudation have generally told so heavily on the forms of the surface that all the conspicuous distinctive features of a volcanic mountain may have been obliterated (though, as will be shown, it by no means follows that they are necessarily always lost), so that by such characters alone they can no longer be recognised with certainty. The prominent cone, the loose cinder-heaps, and the lava-streams themselves are likely to be, to a less or greater extent, removed, and nothing may be often left of the volcanic hill but rugged ridges of the harder streams and

FIG. 193. *Volcanic Cones in Auvergne which have suffered to some extent from Atmospheric denudation.* (Judd.)

dykes, and the vertical plug of the old volcano vent. In districts where the volcanic action has been prolonged to recent or comparatively recent times, there is no difficulty in finding well-preserved monuments, and in recognising the typical forms of the ordinary volcano. But in passing to districts where volcanic action began at earlier periods, and where that action has been longer extinct, the old landmarks needed for our guidance become more and more indistinct.

The Trappean Plateaux of India. Among the districts which present the clearest evidence of volcanic actions, but yet are in no relation with recent eruptions and belong altogether to geological times, are the immense trappean plateaux of the Deccan, which extend east and west for a distance of 400 miles, and 700 to 800 miles from north to south, covering

Dongurgunge.

FIG. 194. *View of the northern flank of the Basaltic Plateau on which Ahmednuggur stands; the Deccan.* (Sykes.)

an area of little less than 200,000 square miles, and this probably was originally still more extensive. They consist of a series of basaltic lava-flows very nearly horizontal, the angle of dip being often less than 1° and constant over large areas. They rise thus gradually from east to west, and attain in the Ghâts a height of from 4000 to 5000 feet, ending in great scarps overlooking the plains of the Konkan coast district[1].

In some of these scarps the traps have a vertical thickness of between

[1] See Medlicott and Blanford's 'Manual of the Geology of India,' 1879, part i. p. 299.

4000 and 5000 feet, and probably, where thickest, of 6000 feet; but the separate flows are of no great thickness. The prevailing rock is some form of dolerite or basalt, sometimes very fine-grained (anamesite), at others coarsely crystalline, and often amygdaloidal. It is seldom columnar. Trachytic rocks are rare. Beds of volcanic ash (and agglomerates) are common, and appear most prevalent towards the upper part of the series. They are much altered, differing but little in appearance from the basaltic lavas, but exhibiting a brecciated structure in weathering. Often a thin bed of ash, and sometimes of bole, intervenes between the basaltic flows. It is a curious fact that no crystals of augite have been observed, except locally in some of the ash-beds, but olivine and magnetite are common. Zeolites of great beauty are found in geodes and cavities in some of these trappean rocks (Poonah).

Sedimentary bands, frequently fossiliferous, are in several places interstratified with the lava-flows. The fossils of the lower intercalated beds are all of freshwater species. Higher in the series a few marine beds occur. The relations of both faunas, though somewhat uncertain, are with the Cretaceous rather than with the Tertiary series. From these facts and from the circumstance that the trappean rocks rest upon beds of Lower Cretaceous age, it is thought probable that the lowest volcanic outflows are of upper Cretaceous age (Turonian or Senonian), while the uppermost were contemporaneous with the Lower Eocene.

Messrs. Medlicott and Blanford consider also that the Deccan traps are of subaerial origin, and that the first lava-streams flowed into shallow lakes; but that, with the constant discharge of lava, the lakes gradually disappeared [1]. They consider that in everything except their horizontality (and this they admit constitutes a great difficulty, because no such formation is known to be in process of accumulation at the present day) and extent, the Deccan traps precisely resemble modern lavas, and that the frequent occurrence, at some places in the very centre of the high plateaux, of ash-beds in the higher traps sufficiently attests the neighbourhood of the old volcanic vents. Nevertheless, nothing in the character of an ordinary volcano has been discovered. It may be contended that the loose materials forming the original cones and crater had, in the long period that has elapsed since Eocene times, been altogether removed by denudation; yet volcanic cones have been elsewhere preserved by encasement in subsequent lava-flows or otherwise protected. It is also pointed out, that in Cutch and the lower Narbada valley, outside the trap-area, there is evidence of volcanic cones; while there is no evidence of any having existed in the Nágpúr country or to the south-east. On the other hand, the

[1] See also Messrs. Hislop and Hunter's paper on 'The Geology of Nágpur,' Quart. Journ. Geol. Soc. vol. x. p. 345, and vol. xvi. p. 154.

authors observe that a considerable area is traversed by numerous large and nearly parallel basaltic dykes, and they add that it is probable the Deccan traps may have flowed from vents without the formation of volcanic cones.

In the Rajmahál district there is a considerable thickness of older bedded basaltic traps, interstratified with sedimentary beds containing plants belonging to the Upper Goodwána series, which beds are probably of Jurassic age. These traps, like those of the Deccan district, are almost horizontal, and the area abounds with dykes that are newer than the faults of the Raniganj coal-field, the region to the north of which seems to have been one of the foci of eruption. No mention is made of the remains of cones or craters.

British Isles. When we come to districts which, in addition to the ordinary meteoric actions, have suffered from glacial denudation, or have been submerged since the volcanic eruptions took place, the obscurity respecting their nature is greatly increased, and the problem becomes open to more divergent interpretations. Such is the character of the old volcanic phenomena of the British Isles, of which we select a few of the more striking instances as examples, but without endorsing in full all the opinions of the authors.

Scotland. Among the most interesting of the old Tertiary volcanic areas is the one that forms a very conspicuous feature in the Western Highlands. In a valuable paper[1] on the Secondary rocks of Scotland, Professor Judd has described five volcanoes, the ruins of which now exist in this district. The most instructive of these is the ancient volcano of Mull, in which not only is the history of a volcano traced, but its internal structure is laid open, as it were, by dissection, and the relation of the different rocks traced in a way impossible in more recent volcanoes.

The Isle of Mull, including the adjacent part of the district of Morvern, constitutes a tract about 25 miles long by 20 broad. This, with various small surrounding islands, forms portions of a great broken plateau of basaltic lavas, piled one upon another to the depth of nearly 2000 feet. In the centre of this plateau rises a group of mountains, about 12 miles across, and attaining, in Ben More, a height of 3172 feet (Map, Fig. 195).

According to Professor Judd, the base of this great central group consists of a micaceous granite, passing into a hornblendic variety, and then by insensible gradations upwards and outwards into felsite. Lying on the skirts of these central masses are thick sheets of felstones, alternating with beds of scoriæ, lapilli, and ashes, with included blocks of the sedimentary rocks of the island, such as might represent the ordinary materials ejected from a volcanic vent. These, with the central granites and felsite, which

[1] 'Quart. Journ. Geological Society,' vol. xxx. 1874, p. 220.

give off numerous veins both into the overlying felstones and the surrounding older strata, are the products of a first great eruption of acidic rocks. Rising through their midst is a newer mass of gabbro and other basic rocks, from which proceed innumerable veins, sheets, and intrusive masses, that penetrate the surrounding siliceous rocks in every direction. In the deeper parts of these intrusive masses of gabbro, diallage and hypersthene predominate; but these minerals are replaced in the peripheral portions by various forms of augite. As the veins of gabbro proceed from the central mass they are found to graduate into coarse dolerites, and through them into basalt. These veins often intersect alike the lavas of the great plateaux, and the various sedimentary rocks which underlie the eruptive rocks.

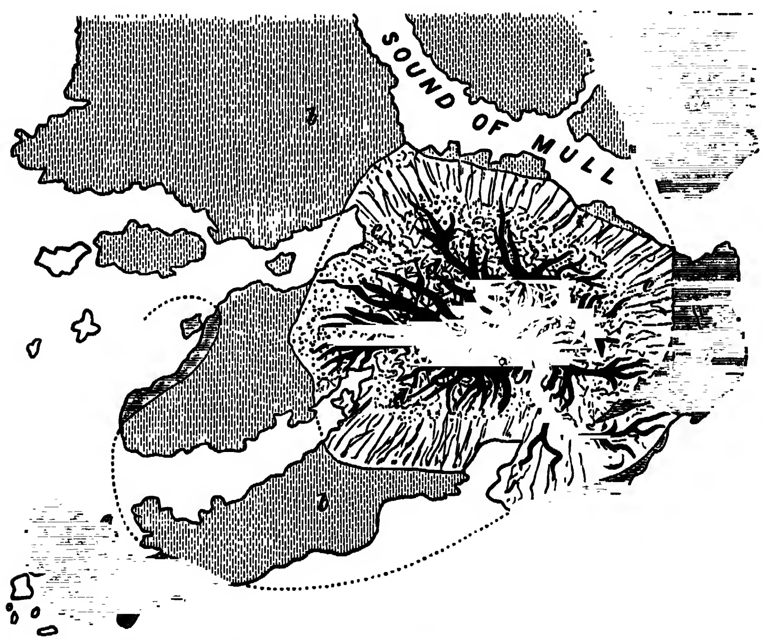

FIG. 195. *Plan of the Volcanic district of Mull.* (Judd). One inch = 8 miles.
a. Palæozoic and Crystalline Rocks. *b.* Basalt. *c.* Gabbro, of Miocene age. *d.* Granite and Felsite of Eocene age.
e. Volcanic Agglomerates of Eocene and Miocene age.

Forming the summit of Ben More, and resting unconformably upon the granite, gabbro, and basalt, is a mass, several hundred feet thick, composed of basaltic scoriæ, tuffs, and ashes, alternating with lava-sheets, and intersected by a plexus of dykes. Where the agglomerates thin out the basaltic lavas come together in one thick mass. In the fissures of the ejected blocks lying in the agglomerates are many beautiful minerals of the same kind as those found in similar positions in existing volcanoes. The entire absence of ejected blocks of the sedimentary rocks in these later

agglomerates, when contrasted with their abundance in the earlier eruptions, is mentioned as a significant fact. These agglomerates belong to the last vestiges of a volcanic cone formed during the period when the basaltic lavas were ejected.

Professor Judd considers that the rocks of the acidic series were first extruded and consolidated; and that subsequently a fluid mass of basic materials forced its way through them, penetrating at the same time into the innumerable rents and fissures caused by the upheaving force. Where-ever, he says, we approach the central eruptive masses, whether of granite or gabbro, the whole of the sedimentary rocks are found to have suffered great disturbance and intense metamorphism—the limestones passing into saccharoid marble, the sandstones into quartzites, and the shales into a hard compact rock (lydian stone or lydite of authors).

He concludes that the mountain group occupying the central portion of Mull is the greatly denuded core of an immense volcanic pile; the thick accumulations of scoriæ and lavas which formed a large portion of this mountain-mass having been to a great extent removed, and what now remains being little more than the skeleton or framework of the vast pile, formed by the consolidation of the springs of liquefied rock which rose through its mass. He thinks that the first eruptions may have taken place at the commencement of the Tertiary period; and that they consisted of great volumes of felspathic ashes and scoriæ, accompanied at intervals by the outflow of streams of trachytic lavas, now forming the felstones. Where this fluid matter consolidated slowly and under great pressure it gave rise to masses and veins, first of granite and then of felsite, and therefore that we have here a granite of Tertiary age.

This period was followed by one of inactivity, during which the first-formed cone lost its symmetry, and denudation removed a large portion of its agglomerates and lavas, whereby the more deeply-seated granitic rocks and felsites of the central core were exposed. The second period of eruption took place during the Miocene period. The more fluid basic lavas of this age, instead of being confined, like those of earlier date, to the neighbourhood of the volcano, flowed to enormous distances; and the successive streams, which were interrupted by long times of weathering, forest-growth, river-gravels, and lacustrine deposits, gradually accumulated to the thickness of 2000 feet.

Subsequent to the eruption of these basic rocks, the great volcano of Mull gradually fell into a state of decay and ruin, when another series of volcanic outbursts of a sporadic character took place, and gave rise to the formation of numerous comparatively small cones, with their accompanying lava-streams, analogous to the secondary and later cones (*puys*) of Auvergne. One of these volcanic cones which rises on the great plateau of basalt, three miles S.W. of Tobermory, now forms the hill of Sarsta Benn.

Professor Judd estimates that the Mull volcano must have had a circumference of at least 40 miles, and that its height was probably not less than 14,500 feet. The removal of the greater part of this huge pile by denudation, while obliterating the distinctive subaerial features of a volcano, has exposed in a way that cannot be seen in any modern volcano the internal structure of a volcanic mountain. It throws new light upon some most difficult problems in physical geology and petrology, and affords a most instructive example of what may be the basal wreck of a great volcanic pile.

The **Jurassic** period in Britain and in Europe generally was one of volcanic inactivity, except apparently in Greece and Italy. Volcanic action was, however, rife in India, Abyssinia (?), and Eastern North-America. Basic rocks prevailed. In America they consist largely of diabases.

Nor does the **Trias** in England exhibit traces of volcanic action, except in one instance described by De la Beche [1], and which is of interest from its being one of the first cases where the characters of a subaerial eruption were recognised in the older formations. In the lower part of the New Red Sandstone at Washfield, near Tiverton, in Devon, the ordinary sedimentary matter is mixed with angular fragments of trappean rocks, some of large size, which De la Beche considered to have been ejected, as in modern volcanoes, from craters in a state of activity during the early Triassic period. The trap-rock of Killerton near Exeter he refers also to an eruption of the same date, and as marking the site of the pipe of an old volcano.

In the **Permian** period there were eruptions of volcanic rocks, on a limited scale, in Staffordshire, Warwickshire, Shropshire, and probably Somerset. In Scotland the volcanic phenomena of this period are on a large scale. Dr. A. Geikie states [2] that in Ayrshire the Carboniferous rocks are pierced with volcanic vents, and overspread with sheets of lava and tuff of Permian age.

The **Coal-measures** present several instances of contemporaneous volcanic action. The intrusive basaltic rocks of the Staffordshire coalfield, and the erupted mass at Rowley Regis, the intrusive diorite rocks of the Warwickshire coalfield, and the basalt of the Clee Hills, are considered to belong to a late period of the Coal-measures, or they may more probably have been accompaniments of the disturbances which intervened between the Carboniferous and the Permian period.

The position of these masses of igneous rock, the intrusive character of which has been clearly proved in various workings in Staffordshire, Leicestershire, and Warwickshire, is very curious, and is clearly shown in the neigh-

[1] 'Proc. Geol. Soc.,' vol. ii. 1835, p. 196.
[2] 'Geol. Mag.,' vol. iii. 1866, p. 243.

bourhood of Dudley and in the well-known Rowley district. The following Fig. 196 gives the diagram section of one of these intrusive masses of basalt in the Coal-measures of the Staffordshire coalfield.

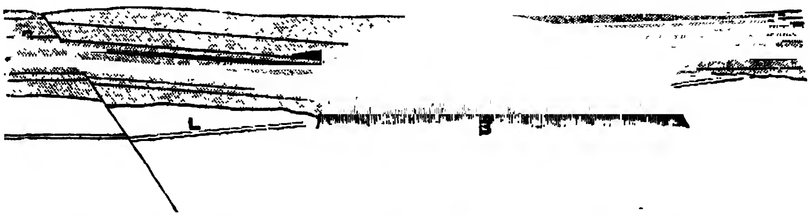

FIG. 196. *Diagram section in the Coal-measures at Hunt's Mill, 2 miles west of Dudley.* (Geol. Survey, ⅛.) *C.* Coal-measures. The thick line represents the thick or 10 yard coal seam. *L.* Ludlow Shales, and Sedgley Limestone. *B.* Basalt.

The **Early Carboniferous** period was a time of great volcanic activity, especially in Scotland and Ireland. The well-known 'toadstones' of Derbyshire, which are bedded masses, generally from about 50 to 80 feet thick, of compact and amygdaloidal basalts, interstratified in the Carboniferous Limestone, were contemporaneous lava-streams, in some places scoriaceous.

FIG. 197. *Section of Toadstones* (*t*) *between Deepdale and Taddington, Derbyshire.* (Geol. Survey, ⅛.)

The Carboniferous Limestone of counties Limerick and Tipperary exhibits, according to Professor Hull, two successive outbursts of volcanic materials [1]. During the earlier, felspathic lavas, along with quantities of ash and lapilli, were extruded; during the second, basalts and melaphyres were poured out. Many old necks, through which the ancient lavas and ashes were erupted, and which are now filled with solid trap, may still be recognised.

The most remarkable display, however, of volcanic action of this age is that which took place in Scotland during the deposition of the Carboniferous strata of the Basin of the Frith of Forth, which have been described in an important paper by Dr. Archibald Geikie [2]. This site seems to have been the scene of numerous volcanic eruptions, producing showers of tuff and streams of lava from towards the end of the Old Red Sandstone period to the end of that of the Carboniferous Limestone, when they ceased. These old Carboniferous volcanic rocks are grouped under four subdivisions: 1. Necks; 2. Intrusive sheets, dykes, and veins; 3. Interbedded or contemporaneous lavas; 4. Tuffs.

In East Lothian there are numerous old volcanic orifices with necks of agglomerate, basalts, and porphyrites, such as now form North-Berwick

[1] 'The Physical Geology of Ireland,' 1878, p. 35.
[2] 'Trans. Roy. Soc. Edinb.,' vol. xxix. 1880, p. 479.

Law and probably the Bass Rock. In Fife, the interstratification of volcanic materials with estuarine beds, coal-seams, and limestones can be admirably studied between Burntisland and Kinghorn; and nowhere, Dr. Geikie remarks, are the characters of true lava-streams more strikingly displayed than in the two miles of shore between Pettycur and Seafield Tower. He estimates the intrusive basalts, which are confined within a limited area, to have a total thickness of 1500 feet. The East-of-Fife district contains an extraordinary number of volcanic vents, there being between Leven and St. Andrews, in a tract of 15 miles by 6, about fifty such orifices.

Streams of porphyritic lavas which, if united, would form a mass over 1000 feet thick, constitute the prevailing type of the volcanic accumulations of this Carboniferous district. They form continuous sheets, covering wide spaces, and rising into conspicuous hills. There is but little tuff mixed with the outpours in this area.

The necks vary from a few yards to a mile in diameter. They contain tuffs, penetrated by veins and dykes of lava, together with débris of the rocks through which the necks pass. The lava blocks in the tuffs are generally rounded or subangular, owing to the attrition they underwent when thrown up. These tuffs belong to the interior of the craters and the upper part of the volcanic funnels, while the basalt and porphyries belong to deeper and more central parts. Kincraig, west of Elie, is mentioned as a fine example of a neck of basalt. Arthur's Seat is regarded as the top of a neck of lava of this age. Sometimes the surrounding dykes of basalt seem to centre in a neck or crater. Instances are given in which the ground-plan of a volcanic neck is laid open by exposure on the sea-shore. An illustrative case occurs at Newark Castle near St. Monans, Fig. 198.

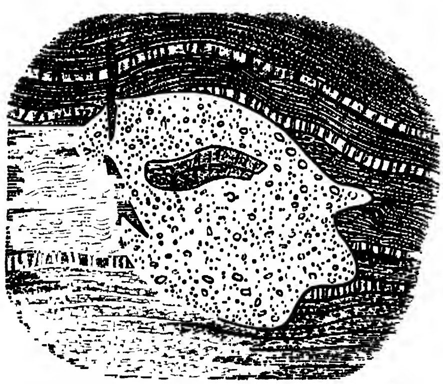

FIG. 198. *Ground-plan Section of the neck of an old Volcano on the shore near St. Monans, Fife.* (A. Geikie.)

The encasing rocks consist of shales, sandstones, limestones, and thin coal, dipping at an angle of 25° to 60° S. The neck of the volcano is filled with tuff and volcanic agglomerates in which a block of the sandstone is enclosed.

A peculiar feature connected with the necks, and for which it is not easy to find a satisfactory explanation, is, that generally, no matter what may be the normal dip, a remarkable change is observable immediately round the edge of each vent, the beds being bent sharply *down towards the wall of the neck.* The tuff in many necks suggests subaerial rather than subaqueous stratification. Fragments of wood are found in some. At

other times, as in section at Pettycur Point,—where, in a thickness of less than two feet of rock, there are twenty-three alternating seams of tuff, shale, and limestone,—the conditions clearly must have been subaqueous. There are instances in which the 'necks' or plugs of the old flues in most cases stand, as it were, on mere denuded stumps of volcanoes; and, the superincumbent cones having been swept away, the very roots of the volcano can be examined. At other times a considerable portion of the old volcano with its tuff and scoriæ beds seems preserved, as in the Saline Hills, Fig. 199, which rise to the height of 1178 ft. above the sea-level.

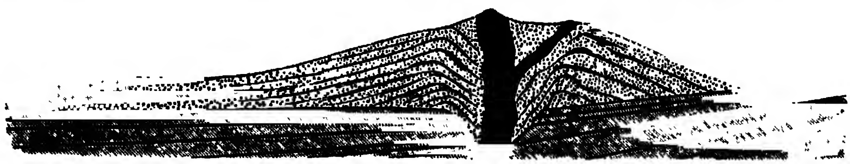

FIG. 199. *Theoretical Section through the Saline Hills, Fife.* (A. Geikie.)

The neck here is of basalt, and is surrounded by beds of volcanic tuff and agglomerates, intercalated in the lower part with beds of early Carboniferous age, as though the volcano had been in eruption in an old lagoon of that period. Coal and ironstone are worked in places under the tuff.

Another case of peculiar interest is the sketch given by Dr. Geikie of Largo Law hill (Fig. 200), for it shows, in connection with the above section (Fig. 199) that, notwithstanding the great age of the volcanoes and the ex-

FIG. 200. *View of the old volcanic hill of Largo Law, taken from the east side. The crag on the left at the base of the cone is a portion of a basalt-stream.* (A. Geikie.)

cessive denudation of the district, it is possible for both the outline and the internal structure of a volcano to be sufficiently well preserved as to exhibit one and the other in a form still recognisable without much difficulty, and therefore that the argument based on the destructive effects of weathering and age to account for the entire absence of crater mountains in certain old volcanic areas is not conclusive.

The intrusive sheets and dykes of Carboniferous age in this part of Scotland vary in thickness from 150 to 350 feet; they consist of diabase, dolerite, and basalt, and are distinguished from the superficial lava-streams by their more crystalline character, and by the absence generally of cellular

or amygdaloidal texture. The sandstones in contact with them pass into quartzite; shales into porcellanite; and coals into soot or anthracite; while the adjacent strata are often much crumpled and broken, as shown in the following sketch.

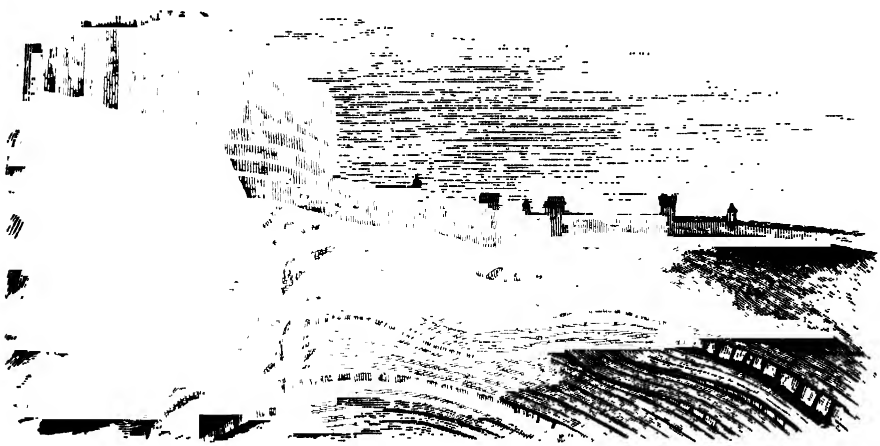

FIG. 201. *Section of a basaltic dyke passing through Carboniferous rocks, under Edinburgh Castle.* (From an old engraving.)

Sometimes, when the intrusive sheets are largely developed, there are few or no volcanic pipes; but no satisfactory relation can be established between those sheets and the volcanic centres. At Arthur's Seat, the lowest volcanic rocks are intrusive sheets,—the upper, erupted lavas and tuffs. At Burntisland it is the reverse.

The dolerites form intrusions and surface-streams. To the former, which are rarely amygdaloidal, the term dolerite is more usually applied, while the latter are termed basalts. There is no apparent difference between these Carboniferous dolerites and those of Tertiary age. All the Carboniferous lavas belong to the basalt section. The great east and west Miocene dykes of Scotland are typical dolerites.

The diabases or granitoid type of the augitic-felspar rocks never form surface lava or streams, but are always intrusive or in bosses.

There are few felsites, and they are all intrusive masses, seldom porphyritic. They are confined to necks and their vicinity, occurring also as dykes and veins. They do not seem to have been erupted on the surface except as showers of felsitic tuff. The prevailing type, however, of the intrusive volcanic accumulations of the Carboniferous system are porphyritic lavas. They always occur as contemporaneous or interbedded rocks, and form enormous sheets. The lavas of the Old Red Sandstone are of the same character.

The tuffs have been formed, according to Dr. Geikie, by the showers of dust, sand, and lapilli ejected from the volcanic vents; falling into

lakes, rivers or sea, they sank to the bottom of the water, where they accumulated in layers more or less mixed with the ordinary sand, mud, or other deposits. They form beds varying in thickness from paper-layers (mere laminæ) to beds several hundred feet thick, and sometimes containing organic remains. The tuffs and *agglomerates* occur interstratified with bedded lavas or with ordinary strata, and also filling up the interior of the craters and the upper part of the volcanic ducts.

As an instance of subaerial ash deposits, we may notice an interesting coast section in the Isle of Arran described by Mr. Wünsch [1]. It shows a series of Lower Carboniferous strata dipping at an angle of 37°, in some beds of which stumps of trees (*Lepidodendron*, *Sigillaria*, etc.), 1½ to 2 feet in diameter and 2 to 3 feet high, stand erect above the thin seams of coal and shale, upon which they grew. The strata in which they are imbedded consists of a trappean ash, of which there are ten beds, all containing branches and impressions of the plants. Some of the trees must have been hollow before they were entombed, for the centre is filled up with vegetable débris and cones. The ash is much indurated, having the appearance and hardness of ordinary trap rock, and covers up the trees to the depth of 2 to 3 feet.

Devonian. Long, however, before the Carboniferous period the whole of Central Scotland had been the scene of some most stupendous volcanic action. During the time of the deposition of the Old Red Sandstone the wide lake or inland sea, which extended between the base of the Highland mountains and the southern uplands, was marked by two long lines of volcanic vents, from which prodigious volumes of lava and ashes were emitted. Even now more than 5000 feet of volcanic materials can be measured at the north end of the Pentland Hills, and the top is not reached. In the Ochil Hills, a depth of 6000 feet of similar rocks can be seen, and yet without reaching the base. These volcanic materials consist of porphyrites, felsites, and tuffs [2]. In Germany the chief volcanic rocks of this age are diabases.

Silurian. There were two principal epochs of volcanic eruption during the Silurian period in Wales,—the later of Bala or Caradoc age, and the earlier of Llandeilo and Arenig. Besides the volcanic rocks of Caer Caradoc and its vicinity, there are others near Bala, where thin bands of volcanic ashes set in below the limestone. In proceeding northward these bands thicken and become mingled with beds of felstones, the mass of which culminates in Snowdon and the surrounding area, extending thence to Conway. It is in this district that Ramsay places the roots of the volcanoes whence the explosive force of steam drove out the lavas and

[1] 'Geol. Mag.,' vol. ii. p. 474, and vol. iv. p. 551.
[2] A. Geikie, 'Trans. Roy. Soc. Edinburgh,' vol. xxix. p. 441.

showers of ashes which became interstratified with the ordinary sedimentary beds of the period.

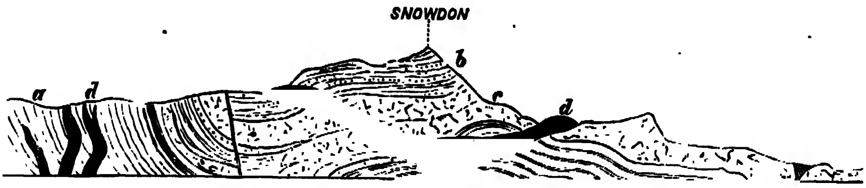

FIG. 202. *Diagram section across Snowdon.* (Ramsay.)
a. Llandeilo and Bala rocks. *b.* Felspathic ashes. *c.* Contemporaneous Eruptive rocks. *d.* Intrusive Greenstones.

Another group of massive felstones, sometimes vesicular, with interstratified ash and tufa, and forming a mass of rocks not less than 2800 feet thick, centres in the Arenig and Llandeilo district of Cader Idris. These rocks, which Ramsay considers to be of submarine origin, are very local, thinning out at no great distance northwards, and are there replaced by ordinary sedimentary strata.

Amongst the most remarkable masses of the volcanic materials of this date are the green slates and porphyries of the Lower-Silurian series of Cumberland, described by the late Mr. Clifton Ward [1]. In the neighbourhood of Keswick and Borrowdale these ash-beds and felstone-like rocks (ancient lavas) are not less than 12,000 feet thick. As these beds are unmixed, except quite at the base, with ordinary sedimentary strata, while all the upper masses are unstratified or but very rudely stratified, Mr. Ward considered that although the eruptions, which were of very long duration, might have commenced beneath the waters of the Skiddaw-slate sea, yet, either by elevation or by partial filling up of the shallow sea-bed, they soon became almost wholly subaerial. The thickness of the separate lava-flows is in general not great; their upper and lower surfaces are usually slaggy and scoriaceous, and in many cases the vesicles, where they occur, are drawn out in the direction of the flow. Their thickness is subject to many variations, but some of the beds may be traced along their present outcrop for a distance of several miles.

Mr. Ward was of opinion that one of the main centres of eruption was close to the present site of Keswick; and that in the low-wooded and craggy hill called Castle Head we see the stump of an old Cumberland volcano, which once poured out its lava sheets and scattered ashy material for many miles around. Denudation, however, has destroyed all semblance of volcanic form; while intense metamorphism has obliterated much of the original character of the volcanic materials.

In Ireland, Professor Hull states there are in the Lower-Silurian strata extensive sheets of felspathic trap, ashes, and agglomerates (felstones, por-

[1] 'Quart. Journ. Geol. Soc.,' vol. xxxi. 1875, p. 405.

phyries, etc.) interbedded with grits and slates. The volcanic action seems to have continued longer than in Wales; for in Ireland there are traps and ash-beds which were vomited forth during the deposition of fossiliferous strata of Ludlow age [1]. These eruptions, like those of the lower-Silurian strata, were probably submarine.

No interbedded igneous rocks have yet been found among the Silurian rocks of Scotland.

Cambrian. In Wales the Lingula-flags and Menevian beds are pierced by numerous dykes and masses of greenstone (diorite) and more purely felspathic traps. It is considered by the Survey that in North Wales these are always intrusive and never interbedded [2].

Pre-Cambrian. Dr. Hicks is of opinion that a very large proportion of the upper pre-Cambrian rocks (Pebidian) had a volcanic origin. Thick masses of agglomerate and quartz-felsites predominate, indicating, he conceives, the proximity of subaerial volcanoes. These rocks amount in the aggregate to a thickness of 8000 feet; and he concludes that at this early geological period volcanic action was even more intense and general than in more recent geological periods; and that the old pre-Cambrian continent was studded with volcanic mountains, and traversed by high ridges and plateaux of volcanic rocks [3].

[1] 'Physical Geology of Ireland,' 1878, pp. 11, 25; and 'Geol. Mag.' for 1874.
[2] Ramsay, *op. cit.*, pp. 85 and 82.
[3] 'Quart. Journ. Geol. Soc.,' vol. xxxiv. p. 160, and 'Geol. Mag.' for Nov., 1880.

CHAPTER XXI.

IGNEOUS ROCKS (*continued*).

NATURE OF THE VOLCANIC ROCKS. COMPARATIVE PETROLOGICAL CHARACTERS OF PALÆOZOIC AND TERTIARY IGNEOUS ROCKS. MOLECULAR ALTERATIONS. ANCIENT FELSITES AND MODERN RHYOLITES. DOLERITES. VOLCANIC MUD-FLOWS. ORIGINAL IDENTITY OF COMPOSITION. EFFECTS OF DECOMPOSITION AND OF DIFFERENCES OF PRESSURE. SUCCESSION OF THE IGNEOUS ROCKS. NATURE OF THE VOLCANIC ACTION. FISSURE ERUPTIONS. THE MEISNER PLATEAU. TRAPPEAN ROCKS. THE CHARACTERS OF CRATER AND FISSURE ERUPTIONS. ABSENCE OF ASH-BEDS AND OF VOLCANIC CONES. HORIZONTALITY OF TRAPS. PRODUCTS OF SUBMARINE ERUPTIONS. ASH-BEDS AND AGGLOMERATES. FISSURE ERUPTIONS FORMERLY PREDOMINANT OVER CRATER ERUPTIONS. SERPENTINE AND OLIVINE ROCKS.

Nature of the Volcanic Rocks. Not long since the belief prevailed, with a few remarkable exceptions (see note, p. 387), that the rocks of the earlier geological periods differed, both in chemical composition and mineral structure, from the volcanic rocks of recent date; but within the last few years microscopic and chemical analysis have shown that such is not, at least always, the case, and that in both respects there is often perfect identity. Still this is not admitted by all petrologists. It is certain that many of the older volcanic rocks now present distinctive differences from the newer ones; but it has been shown that the differences in most cases arise from subsequent alteration or metamorphism of the rock, and are not to be attributed to differences originally existing. The imbibition of moisture which goes on even in the hardest of these rocks, combined with heat and pressure, has in most instances effected such changes in their constitution and aspect as to mask this common origin. While some petrologists hold that these causes, together with differences in the rate of cooling, are sufficient to explain existing differences, others consider that there were initial differences, and that these have not been altogether removed by subsequent changes.

A few years ago Mr. Allport showed [1] that the volcanic rocks (so-called greenstones and others) associated with the Carboniferous strata of the Midland Counties are not to be distinguished in composition or microscopic structure from dolerites and basalts of Tertiary age—that the

[1] 'Geol. Mag.' for April 1870, p. 159; 'Quart. Journ. Geol. Soc.,' vol. xxx. p. 529.

melaphyres of Palæozoic age were identical with many Tertiary basalts, and that many diabases are only altered dolerites. He would, therefore, discontinue the use of the terms *melaphyre*, *aphanite*, *anamesite*, *diabase*, and *greenstone*, and suggests that all the basic augitic rocks should be included in one group under the generic name *dolerite*.

The felspar of this group, which is a plagioclase, although orthoclase is frequently present, undergoes a granular change, whereby it is converted into an amorphous substance no longer possessing the optical characters of the original crystals. The augite is frequently unchanged; but at times it may be partly or entirely altered with the production of grey and green chloritic pseudomorphs. Olivine, which is seldom absent in the rocks of the Midland Counties, is rarely in an unaltered state, and the true nature of its green serpentinous pseudomorphs had not before been recognised. Magnetite, usually titaniferous and which is always present, is often converted into reddish-brown peroxide of iron. Calcite is another product of decomposition.

While the contemporaneous traps of the Carboniferous strata of Derbyshire are much altered, Mr. Allport found that the rock of Pouk Hill, near Wallsall, was, both in its state of preservation and in mineralogical composition, quite undistinguishable from a Tertiary dolerite; and he states that many Tertiary basalts are even in a less perfect state of preservation than some of the Scotch volcanic rocks of older date.

Great variations of texture and composition, however, frequently occur in a single rock, so that specimens, which in the cabinet might pass under different names, may be collected in the same quarry. There is also great irregularity in the relative proportions of the several constituents of these rocks; but these are variations of composition and structure common alike to the Carboniferous and Tertiary rocks of this character.

In Warwickshire there are intrusive diorites in the lower unproductive Coal-measures, one variety of which is of much interest from its containing, as accessory minerals, augite and olivine. Hornblendic rocks of this character have not been found in any other part of Britain, nor elsewhere, except among strata of Tertiary or later age[1].

In a subsequent paper[2] Mr. Allport described the results he obtained with the acidic rocks, which were similar to what he had previously arrived at with respect to the basic. He showed that the reddish-brown felsite of the Wrekin, which is of Palæozoic age, is really an altered or devitrified perlitic pitchstone, which, both in chemical composition and mineral constituents, is identical with the Tertiary perlite of Schemnitz in Hungary; and 'it appears also that in the older as in the younger series there is the same gradation between the vitreous and the stony varieties of these rocks.'

[1] 'Quart. Journ. Geol. Soc.,' vol. xxxv. p. 637.
[2] *Ibid.*, vol. xxxiii. p. 449.

Mr. Rutley also found perlitic structure in some of the felstones associated with the Bala beds of North Wales, and considers that they were once vitreous lavas. He concludes that, in many cases, felstones are essentially devitrified hyaline rhyolites, although it seems impossible to demonstrate that they are so in all cases[1].

With respect to another class of Tertiary rocks with a more or less vitreous structure, an examination of the pre-Cambrian rocks of Wales led Professor Bonney to the conclusion 'that, allowing for slight mineral changes brought about by the agencies to which all rocks have been exposed in the long lapse of ages (such as devitrification, the formation of viridite, etc.), there is no difference of any importance, as far as he could see, between those ancient quartz-felsites, and the comparatively modern rhyolites, and that they were rhyolites in pre-Cambrian times[2].' These old rock-masses, which seem to be of exceptional thickness and extent (one being about thirteen miles long and two at greatest breadth), are associated with volcanic agglomerates. The outbursts in the several areas were probably very local. Elsewhere Professor Bonney observes of the porphyries or quartz-felsites of North Wales, that these rocks present the usual characteristics of lava-flows, 'such as fissile jointing, fluidal structure, etc.,—that they are in one place apparently interbedded with slate, at another associated with a true agglomerate,—that microscopically they show fluidal and other structures of rhyolite so perfectly that (except perhaps for their devitrification) we could imagine them to be no more ancient than the rhyolites of the Euganean Hills or of Hungary.' He also shows that, as fragments from these lava-rocks are abundant in other overlying pre-Cambrian strata, they must be of contemporaneous age[3].

Mr. J. A. Phillips[4] has also shown, by a series of combined chemical and microscopical analyses, that the old so-called 'greenstones,' which protrude through or are interbedded in the killas or clay-slates of Cornwall, are ancient 'dolerites or gabbros in which the originally constituent minerals are occasionally to a great extent unchanged, but are sometimes almost entirely replaced by pseudomorphic forms.' Other of these rocks would indicate that they are probably altered ash-beds, or hardened hornblendic slates. He likewise found in central and northern Cornwall supposed ancient lava-flows, interbedded with the slates and schists. They have undergone great alteration, such as the transformation of the augite into hornblende and viridite; of the felspar into a granular mass; and of the titanic iron into a light greyish product; but, notwithstanding this, these lavas closely resemble those of more modern date, having, like them,

[1] 'Quart. Journ. Geol. Soc.,' vol. xxxv. p. 508.
[2] *Ibid.*, 1879, p. 310.
[3] Lecture read before the Phil. Soc. Birmingham, 1879, p. 10.
[4] 'Quart. Journ. Geol. Soc.,' vol. xxxii. p. 155, and vol. xxxiii. p. 493.

often been vesicular, and the cavities being now filled with calcite, viridite, chlorite, and quartz.

The same mode of investigation has led Mr. Phillips to believe that a peculiar foliated felspathic rock in North Wales, containing a large percentage of manganese and overlying a more acidic, crystalline, and less altered rock, may be the result of a flow of volcanic mud, from which a portion of the silica has been removed by water under pressure and at a high temperature; while a uralite-porphyry would appear to be a much altered augite-porphyry or ancient dolerite.

These instances will be sufficient to show that, if not all, at all events a very great part of the series of volcanic igneous rocks which have been either intruded into or extruded through the solid crust of the earth, during all its geological stages, have been alike in composition[1] and seemingly in structure, and that the apparent differences, which now exist between the ancient and modern rocks of this class, are due mainly to secondary causes, such as the conversion of scoriaceous and vesicular lavas into amygdaloidal rocks by the deposition of silica, calcite, or zeolites in the vapour-cavities; and the conversion by some processes of siliceous cementation, combined with pressure, of loose ashes and lapilli into hard and often schistose rocks. On the other hand, certain molecular processes have devitrified the vitreous and glassy obsidians, rhyolites, and pitchstones, and converted them into massive and amorphous felsites and some varieties of porphyry. Similar changes have also in many cases so altered the molecular structure of the constituent minerals that new species appear, and a variety of pseudomorphs are formed, unknown in the more recent rocks.

Conspicuous among the rocks so affected are the Palæozoic melaphyres, which are now considered to be altered basalts. In other cases processes of decay have reduced many of these basic rocks into soft and earthy wackés, while the more acidic rocks have become claystones.

Equally remarkable are the changes effected by depth, pressure, and differences in the rate of cooling. The superficial porous lava may pass downwards into compact basalt; this with the increase of depth into dolerite; and this again into gabbro. Granular trachytes become felstones, and andesites pass into porphyrites. Granite may pass upwards, under lessened pressure and more rapid cooling, into fine-grained quartz-felsite; and, as it reached the surface, some geologists consider that it may possibly have passed into glassy rhyolite and obsidian, and in the same way that

[1] Cordier long since ('Mémoires des Savants Etrangers,' Paris Acad. des. Sc., 1815) proved that the matrix or base (*pâte lithoïde*) of lavas of all ages possessed a micro-crystalline structure, was composed of the same species of minerals, and was identical in structure and composition. He also showed the identity of basalt and dolerite, and considered that under the term *basalt* should be included ordinary and compact lava. He was also of opinion that the glassy lavas of all ages present a perfect identity. The differences observed between certain varieties of modern and ancient lavas of the same nature he attributed entirely to slight modifications in texture dependent on time.

syenite may pass upwards into certain forms of porphyry and into trachyte. The effects of these changes of conditions, dependent on depth, become apparent where denudation has removed large masses of the superincumbent rocks, as in the instances named in the last chapter, and in others; and some geologists are now of opinion that the bosses and veins of many ancient crystalline rocks visible on the surface may be only the deep-seated or basal portions of rocks which, on reaching the surface, passed into non-crystalline and glassy lavas. These questions are, however, still under discussion. It would not, of course, be possible to admit this connection between rocks due to actual igneous fusion, such as the various volcanic rocks, with those like granites, syenites, etc., brought about by hydrothermal action, if we are to adopt that view of their origin.

Each class of these rocks consists of a series of infinite gradations. For the purpose of showing the relation of one to the other they are grouped by Richthofen in a few main divisions which, slightly modified, are shown in the following Table :—

Granitic type.	*Porphyritic type.*	*Volcanic type.*
Granite. Pegmatite.	Quartz-porphyry.	Rhyolite.
Syenite.	Porphyrite.	Trachyte.
Diorite.	Melaphyre.	Propylite.
Gabbro.	Augite-porphyry.	Andesite.
Diabase.		Basalt.

This, however, can only be considered as a very provisional arrangement.

Succession of the Volcanic Rocks. The very concurrent testimony that the ultimate constituents of the several groups of volcanic rocks, whatever may be their geological age, are alike, would show that they have, during all geological time, been drawn from the same sources or magmas. But, with reference to the question whether or not there has been the same relative correspondence in the proportions of the several groups during recent and past times, there is room for more diverse opinions.

There can be no doubt that a large number of the great eruptions of more recent times have been of basic (basaltic or doleritic) lavas. It, however, has been shown (p. 370) that in America they were immediately preceded by highly acidic rocks, while in earlier Tertiary times those of an intermediate character prevailed; and the same order of eruption is said by some to obtain in Central Europe. Again, in Cretaceous and Jurassic times,—judging from Central India, Abyssinia, and North America,—basaltic rocks predominated. The outbursts of Permian times were chiefly of basic rocks. Diabases and dolerites constitute the great bulk of the Carboniferous igneous rocks of Britain and Ireland. Diabases were also

the chief igneous rocks in Germany of Devonian times. But in Silurian times the great outbreaks in Wales and Ireland consisted of acidic felstones; on the other hand, in Cumberland the rocks of that age are chiefly dolerites. In Cambrian times diorites and felspathic traps prevailed, while in pre-Cambrian times acidic rocks of the felsite type were predominant.

While, therefore, it would seem that basic rocks preponderated during Tertiary times, there is nothing to warrant the assumption that the igneous outflows of Mesozoic and Palæozoic times were more acidic than basic. This is apart from the question relating to the so-called Plutonic rocks of the acidic type, which will be considered in the next chapter.

Character of the Volcanic Action. The phase of volcanic action now in force is confined exclusively to the central-crater effusive and explosive form of eruption. But there is every reason to believe that another form—that known as 'fissure-eruption'—was the more powerful, copious, and frequent form of eruption in past times. The molten rock extruded by both modes of eruption being so generally alike in composition, the products in either case have been commonly termed lavas; and it has been customary to speak of lavas and lava-streams, of ash-beds, and layers of scoriæ, and of volcanoes, whatever may be their geological age, in a manner which might lead the student to conclude that all volcanic agglomerates and breccias, together with the bedded masses of volcanic rocks, were ejected or flowed from crateriform and central volcanoes.

Fissure Eruptions. If there are, as I believe, grounds for establishing a difference in the mode of outflow, then, to denote the distinct physical conditions under which the two series of rocks have originated, it would be convenient to distinguish the resultants by different terms. The term '*lava*' in connection with the *central crater-eruptions* of the present day should be retained for all cases where the igneous rock is undoubtedly due to that form of eruption; whilst that which is supposed to be the product of *fissure-eruption* should, I would suggest, be designated by the old term of '*trap*' or 'trappean rocks.' The fact that this term has been long in use, although it has been employed to designate a peculiarity of structure rather than the mode of origin, shows that a difference of some sort was early recognised, and implies cause for the distinction. Thus in the case of the Auvergne district, there are lava-streams and scoriæ-beds clearly related to crater-volcanoes, while the great basaltic plateaux were probably formed by fissure-eruptions, and should be classed as trappean rocks. The old term of 'traps' applied to the Deccan traps[1] is rightly used if we look at them in the sense here designated.

It is not always easy to obtain direct proofs of fissure-eruptions. They must be often dependent on collateral evidence, owing to the circumstance that in most cases the fissures lie buried under the masses

[1] Gilchrist in 'Quart. Journ. Geol. Soc.,' vol. xi. p. 553.

extruded from and extending over them. Where, however, the extrusion happened to be checked at the surface, or where the superincumbent mass has been cut through by rivers or by a coast-line, there is occasionally evidence of the original fissures. Great dykes extend for long distances and often in nearly parallel lines in the high plateau districts of North America and the Deccan of India. The north of England and part of Scotland are traversed by basaltic dykes, in some cases extending from coast to coast, and in most Palæozoic strata dykes of igneous rocks are especially common.

The remarkable plateau of basalt and dolerite which, at Meissner, overlies Tertiary beds and strata of New Red Sandstone, offers the following section[1]:—

FIG. 203. *Section of the Trappean Plateau of Meissner.* (Credner.) *rs.* Red Sandstone; *t.* Tertiary Lignites; *d. Dolerite and Basalt.*

This mass of trap attains a thickness of 300 to 400 feet. Two large dykes, one of which is about 350 feet and the other double that width, with a number of offshoots, and filled with dolerite, and another (not shown) with basalt, proceed downwards through the Tertiary strata and the Red Sandstone. An occasional seam of volcanic tufa separates the trap-rocks from the lignites, which, when in contact with the igneous rock, pass into anthracite or some variety of hard coal; but of true scoriæ- and ash-beds there are none. The basalt is considered to be older than the dolerite.

Trappean Rocks. The proofs of the non-explosive origin, of the massive out-welling, and of the peculiar fluidity of traps, lie in the absence of scoriæ, ash-heaps, and cones over large tracts, and in the wide extent and remarkable horizontality of these rocks. In many of the fine coast-sections of the north of Ireland and western Scotland, the basalt may be seen directly overlying the sedimentary strata, or only separated by a few feet of scoriaceous matter or tuff; and basalt succeeds layer over layer, often with interbedded land- and plant-remains *in situ*, free from explosive ejectamenta. The absence of ashes and scoriæ may be owing either to denudation or to original default. There was doubtlessly subaerial denudation, and valleys and river-channels were excavated during the intervals between the successive eruptions. The intermediate higher ground would, however, have remained unaffected by river-action; and, had explosive materials been ejected, they should be found on the old land surfaces.

[1] Credner, *op. cit.*, pp. 149, 288, 619.

But the vegetation, which then flourished on the land during periods of repose, was covered directly by successive sheets of basalt without the interposition of ash and lapilli, or at least by only such an amount of detrital matter as would result from the decay of the one surface, and the scoriaceous coating forming the under surface of the succeeding sheet,—such as would result merely from contact of the basalt with the moist or wet soil and vegetation of the ground over which it flowed. There is an absence of those alternations of ash and lapilli, and of those irregular lava-streams which are the accompaniments of the ordinary volcano.

It is more than probable also that, had cones and craters existed in connection with such (fissure) eruptions, they would have been more frequently entombed and preserved by succeeding flows of basalt, just as now the secondary cones of Etna are occasionally surrounded and covered up by fresh streams of lava. The small gradients, and consequent small pressure, would have rendered this of easy accomplishment.

To ascribe the obliteration and absence of all traces of those volcanic cones supposed to have existed in connection with the great plateaux of basaltic (trappean) rocks to the effects of weathering and degradation is scarcely a sufficient reason, for I have shown that (pp. 369 and 379) cones and hills connected with true volcanic action of great antiquity have been preserved both in Scotland and America.

Nor is it possible to account for the singular horizontality of trappean rocks on the crater-volcano hypothesis. The beds are comparatively level over vast areas. There is no leading up to a dominant centre. In North America and the Deccan the dip rarely exceeds 1°; whereas, even on the lower slopes of modern volcanic mountains, the dip generally varies from 6° to 8°. The molten mass must have outpoured simultaneously over great breadths with extreme rapidity, and in large and superheated volumes, for it to have retained, for a sufficient length of time, the extreme fluidity which was essential for such wide-spread and level flows.

Besides, the ordinary lava-stream, although often of great length, has always a comparatively small breadth, and radiates from a centre; whereas those vast sheets of trap extend right and left over broad and lengthened tracts and cannot be traced to any common central single point.

Volcanic Tuffs. The masses of tufa interbedded with some traps, as in those of the Deccan and others, need not be necessarily due to explosive action. Such tufas might be formed wherever the molten trap flowed in a fluid condition into water, whether a lake or the sea. When the lava is viscid and flows so slowly that before reaching the water it becomes encased in a chilled crust, little effect is produced by contact with water, as in the instance of the stream from Vesuvius, which advanced into the sea at Torre del Greco quietly, and with very little disturbance; but in the case of the eruption of Mauna Loa, in 1832, when the great lava-stream flowed

into the sea rapidly, and in a state of active igneous fluidity, it was (according to Mr. Coan, who witnessed the eruption) accompanied by loud detonations, and 'the lava was shivered like melted glass and thrown up in clouds that darkened the sky.' Dana, who afterwards visited the spot, found that, owing to the water which ascended at the same time, the structure of the mass of exploded lava débris was 'laminated like the alluvium of a river [1].' The result would necessarily be the same whether the molten rock was that of a lava-stream or of a trap-sheet.

In such cases, also, as that of Graham's Island (Fig. 92), the shivered débris formed by this submarine eruption, and which built up an island 200 feet high, where previously there had been a depth of 600 feet of water, was in the course of a few months removed and spread out over the adjacent sea-bed. The bank thus formed covers an area of about 120 square miles, and where the island uprose there is now a depth of many fathoms. These submarine eruptions are not infrequent; and in these instances the resulting shattered products, whether the eruption were from a central crater or from a fissure, would be undistinguishable unless it be from the circular arrangement of the one, and the elongation of the other.

The products of such submarine eruptions would also to a certain extent simulate the agglomerates, and ash-beds formed by explosive subaerial action. Yet there is no evidence that the eruption of Graham's Island was in any way explosive, even when the island rose above the sea-level. The discharge of steam seems to have been no greater than that which might be produced by the contact of the submarine mass of lava with the sea water, while on the other hand the effect on the lava seems to have been, as with the lava-stream of Kilauea, to shatter the whole mass to fragments. For, not only the island, but its base also must have been built up of such fragments, to have allowed of so rapid an action of the currents, that in a few months the entire structure was removed, and the detrital materials spread of course over a considerable area. No solid core was discovered in any part of the Island.

Beds of submarine volcanic débris may also at times have been formed by the wear and denudation of tracts of ancient volcanic rocks, especially when these rocks had passed, as they so easily do, into a state of decay and disintegration. Ash-like beds, tufas, and agglomerates may have been formed around old volcanic lands in a manner analogous to that which—as a resultant of the decomposition and decay of granite—has led to the thick and extensive sedimentation of arkose round the central granitic plateau of France during the Carboniferous period, or of the beds of the Millstone-grit round the submerged and lost granitic district of central England.

Ash-beds. Just, therefore, as there is reason to object to the too

[1] 'United States Exploring Expedition,' vol. x. pp. 189, 193; 1849.

general use of the word 'lava' in speaking of the volcanic rocks of geological times, in consequence of its implying the existence of a central crater and cone, so there is, I think, for a similar reason, a like objection to the too common use of the terms 'volcanic-ash and lapilli.' There are certain characters in the volcanic rocks as a whole which render their discrimination one of little difficulty; but with the detrital beds there are fewer guiding features. The materials of these latter, whether of explosive or degraded origin, will all exhibit more or less wear, and may have been removed to lesser or greater distances from their source. Judging from modern causes, we should, however, expect the ashes and lapilli of explosive volcanoes to be carried by the winds to greater distances than the ejectamenta of submarine eruptions would be carried by marine currents. Shore deposits are generally confined to a few miles from land, and very rarely extend to a distance of over 150 miles from the coast (Chapter VIII), whereas ashes are carried hundreds of miles by the winds. In the Palæozoic series of strata there is seemingly an absence of evidence of distant transport of ashes or even of pumiceous débris, but this is a point on which we want more data. The fine interlamination of ordinary sediment with volcanic débris has often the appearance of detrital matter carried down from a land consisting largely of volcanic rocks, rather than to being due to intermittent explosions of ash and lapilli from a volcano. Of course where such detrital beds radiate from a centre, and where they slope up to a central point, we may conclude that they were ejected from an ordinary subaerial volcano; or, when we find a cone buried beneath subsequent trap- or lava-flows, or by sedimentary strata, the fact becomes patent. But these cases are few; and it seems to me more than probable that a large portion of the so-called ash-beds and agglomerates are due to submarine eruptions and inruptions, or to weathering of ancient lands, denudation, and sedimentation, rather than to subaerial explosions.

The presence of volcanic bombs and of fragments of stratified and foreign rocks indicates, of course, explosive action, but that action may have been from small parasitic or secondary cones formed along lines of fissure, as on Etna and on the basaltic plateaux of Auvergne, and not that connected with the prolonged and powerful action of a great central cone and crater. Nor does fissure-eruption otherwise altogether exclude irregular explosive action. No fissure can be formed through the sedimentary strata without meeting some water-bearing beds, so that such fissures would, if left open, have been gradually filled with water, as we have shown was the case during the formation of mineral veins.

Where the rents in the crust have extended to such depths that they tapped the molten magma beneath, and the fluid mass has risen in the fissures, explosions must necessarily have followed wherever water was met with, and have been violent and continuous, in proportion to the

quantity of that water. With the persistent rise of the molten rock, whether to the surface merely or outwelling over the adjacent country, the springs of water would become sealed, as it were, and stopped up, and the explosions would be confined to the effects of the first contacts, and the ejectamenta restricted to areas small in comparison with those covered by the powerful detonations and explosions of the modern sub-aerial volcano. The narrow limits to which some of the old detrital volcanic materials are confined are seen in the frequent rapid thinning off of great masses of volcanic rocks and tufa, as in the instance of the thick beds of such rocks in the Lower Carboniferous Limestone of Bathgate, near Linlithgow, that are non-existent at Blackburn, although the two places are not three miles apart [1]; and in the case of the volcanic ashes and felspathic lavas of Cader Idris [2], which are there 2800 feet thick, and yet thin out so rapidly that a few miles northward they are entirely replaced by ordinary sedimentary strata.

I therefore conclude that the mode of volcanic action in past geological times was in great part essentially different from that of the modern volcano. There is every appearance that the extravasation of the molten rock was more vigorous and frequent; while, on the other hand, the vast pile of the modern volcanoes and the energy and force of their great paroxysmal explosions exceed those of the true volcano of past geological periods. The crater-eruptions, indeed, seem to have gradually increased in force as we approach our own time. It was not then, as now, a long-maintained and violent contest between the power of fire and water, but short and decisive actions, in which the issue never remained long doubtful.

Serpentine and Olivine Rocks. We have reserved these rocks for separate notice, because, although often massive and intrusive, the origin of Serpentine has been a contested point, and a variety of this rock is frequently of sedimentary origin [3], and the result of metamorphism. In its latter condition, it forms thick beds in the Laurentian and other metamorphic rocks, of which we shall treat in the next chapter.

The peculiarity of ordinary serpentine is that, although it possesses such well-marked characters, it is not a native rock, but is a rock due to the subsequent alteration not of one, but apparently of various igneous rocks, of which lherzolite is one of the most prominent. It seems to present a case analogous to that of those mineral veins previously described (Chapter XVIII), in which the action of the surface-waters has led to the formation of oxidised and hydrated products very dissimilar to the original mineral substances. This change, to which we owe one of our most beautiful ornamental stones, is confined to a group of highly basic rocks, in which olivine enters largely, either as an essential or as a secondary constituent.

[1] A. Geikie, 'Trans. Roy. Soc. Edinb.,' vol. xxix. p. 505.
[2] Ramsay, 'Mem. Geol. Survey,' vol. iii. 2nd edit., chapter v.
[3] This variety of serpentine generally constitutes the form known as *ophicalcite*.

The change from olivine rocks to serpentine is effected by the hydration of the magnesian silicates, and by the loss of a portion of their magnesia. By fusing some serpentines with the addition of magnesia, M. Daubrée has obtained a crystalline mass having the general characters of olivine[1].

Some of the old lava-streams in the Isle of Bourbon consist of a basalt, rich in olivine, which passes into a serpentine; and in some of the older Würtemberg basalts (as at Höwen) the alteration of the olivine and augite has produced a rock which is little more than a serpentine containing magnetite[2]. The dunite of the Vosges, which is probably of Permian age, passes into serpentine; and in the French Alps, according to M. Lory, there is a dyke of amphibolite which passes into diallage rock, and then into serpentine, which protrudes in thin veins into the Trias[3].

The serpentines of the Ligurian Apennines, which form a large mountain massif, and are of late Cretaceous or early Tertiary age, have been shown by Professor Bonney to be identical in general characters with the Palæozoic serpentines of the Lizard, and, like them, to be a more or less altered igneous olivine rock. The intrusive character of the former is proved by the disturbances caused in the surrounding strata, and by the blocks of altered sedimentary rock (probably Upper-Cretaceous) included in the serpentine. At some places the walls have been crushed and recemented, forming a fine breccia. Intrusive in the serpentine here and elsewhere are frequently dykes of gabbro. This association has led some observers to consider serpentines to be the result of transmutation of gabbro, but this view is rejected by Professor Bonney, although he considers the association of the two rocks to be a remarkable feature[4].

In the upper valley of the Reno nummulitic strata of Eocene age are penetrated by dykes and bosses of diallage rock, which have pushed before them fragments of sandstone and limestone, of all sizes, forming true friction-breccias. The limestones in contact are converted into dolomites and serpentinous marbles, and the argillaceous beds into jaspers[5].

The great mass of serpentine forming the Lizard is shown, for the same reasons, by Professor Bonney, to be an intrusive rock. It contains fragments of the hornblende schist through which it has burst; and, in its turn, it has been broken through by dykes of granite, gabbro, and dolerite. From the presence in the Lizard serpentines of enstatite, an augite, and picotite, all constituents of the typical lherzolite of the Pyrenees, Professor Bonney concludes that the original Cornish rock was of that character, and that the alteration into serpentine has been effected by the action of water

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[1] 'Comptes Rendus,' vol. lxii. p. 660, 1866.
[2] Rutley's 'Study of Rocks,' p. 117.
[3] De Lapparent, *op. cit.*, p. 1141.
[4] 'Geol. Mag.' for August, 1879, p. 362.
[5] Coquand, quoted by De Lapparent, *op. cit.*, p. 1156.

not necessarily at a high temperature. He is also of opinion that the intrusion of the lherzolite was probably of later Devonian age, the gabbro and granite of Carboniferous, and the basaltic dykes of Triassic age[1]. That the lherzolite of the Ariège was also intrusive, is concluded from its penetrating the surrounding Jurassic limestone, which it has converted into a saccharoid marble, and from the existence in places of a friction-breccia of both rocks; but there is no proof of actual volcanic eruption[2].

The probability that an olivine rock like lherzolite is a deep-seated rock is supported by the observations of M. Daubrée, who describes the occurrence[3] of angular fragments, some of large size, of olivine in various basalts—fragments which he refers to fracture from masses of deep-seated lherzolites. In lherzolite olivine is combined with enstatite, an augite (diallage or diopside), and chrome-iron, all of which are present in serpentine, although the olivine is generally entirely changed; but, as Professor Bonney has pointed out, there are often undecomposed portions of this mineral still to be detected, even in the serpentine of the Lizard. The change into serpentine commences with the olivine, next attacks the enstatite, and finally the augite or pyroxene.

Great importance is to be attached to the group of olivine rocks, of which M. Daubrée would constitute a separate family. Their highly basic character and their great density form features distinguishing them from all the other eruptive igneous rocks, and renders it probable that they are very deep-seated. These differences are indicated in a general way in the following list, which gives approximately the relative mean proportion of silica and the densities of the more important groups of igneous rocks:—

	Proportion of Silica: Mean quantity.	Mean specific gravity.
Rhyolites ...	74·5	2·45
Trachyte and Obsidian ...	68·5	2·53
Porphyrites ...	62·5	2·70
Diabase and Diorite ...	52·0	2·80
Basalt and Dolerite ...	49·0	3·00
Gabbro and Diallage Rock ...	46·5	3·10
Lherzolites ...	41·2	3·35

1 'Quart. Journ. Geol. Soc.' for November, 1877, p. 884.
2 'Geol. Mag.' for February, 1877.
3 'Comptes Rendus' for March, 1866, p. 665.

CHAPTER XXII.

METAMORPHISM.

METAMORPHISM. CONTACT-METAMORPHISM. EFFECTS OF BASALTIC INTRUSIONS; DYKES; WHIN-SILLS; TOADSTONES. GREENSTONE INTRUSIONS. THERMAL EFFECTS. MINERALS PRODUCED. ACTION ON CRYSTALLINE ROCKS. GENERAL RESULTS. CONTACT-METAMORPHISM IN CONNECTION WITH THE SO-CALLED PLUTONIC ROCKS. THE ACTION OF GRANITE. DEGREE OF HEAT. CONTACT WITH SYENITE. REGIONAL-METAMORPHISM. EFFECTS OF ROCK-CRUSHING. HEATING OF ROCKS IN DISTURBED AREAS. EXAMPLES AT DIFFERENT TIMES. RESIDUAL HEAT. NORMAL-METAMORPHISM. TEMPERATURE AT DEPTHS. VARIOUS PERIODS OF METAMORPHISM. SCHISTOSE AND GNEISSIC ROCKS OF ARCHÆAN AGE. ATMOSPHERIC PRESSURE AT FORMER PERIODS. TEMPERATURE OF THE EARLY OCEAN WATERS. CHEMICAL SEDIMENTS. MINERALS OF THE METAMORPHIC ARCHÆAN ROCKS.

Metamorphism is that molecular and structural change in the strata of the sedimentary series, or in the rocks of igneous origin, whereby they have undergone a transformation in the chemical combination of their elements, in mineral constituents, and in structure, so that their original condition has been more or less modified and altered, and their characters disguised. In a certain sense this may be the state of almost all stratified rocks, to which we will at first confine attention, since few remain in the condition in which they were first deposited,—a large proportion having undergone some change, besides cementation and segregation, either by calcareous or siliceous infiltration or by pressure, or by both combined. The use of the term 'metamorphism' is, however, restricted to those greater chemical and mineral changes, caused by heat combined with pressure and moisture, which have resulted in more radical alterations. These may be brought about by heat due to local conditions, or by that dependent upon more general causes. The one produces the effects known as *contact-metamorphism;* the others, as *regional-metamorphism* and as *normal-metamorphism.* The first of these terms has a definite and well-understood meaning; but, in the application of the last two, I have proposed to make certain changes so as to give each term a more special and restricted signification[1].

Contact-Metamorphism has resulted from juxtaposition of the strata with heated volcanic, trappean, and plutonic rocks. It has already been stated (p. 207) that where sedimentary rocks are in contact with

[1] Proceedings of the Royal Society for June, 1885.

hot lava, they undergo a change both in aspect and in structure. Limestone is rendered crystalline and converted into marble, argillaceous strata into porcelain-jasper and hornstone, wood into charcoal, lignite into coal, coal into coke or soot, and sandstone into quartzite; while new minerals are often generated in the altered rock.

The well-known experiments of Sir James Hall proved, years ago, that common earthy chalk subjected, in closed iron vessels, to great heat and pressure, was converted into a white crystalline marble; but laboratory experiments too generally fail to yield the products formed in nature under conditions of pressure, saturation, and time which are unattainable by artificial means, although they serve to corroborate the assigned causes of the phenomena. In the case, however, of those volcanic rocks, the igneous origin of which is well established, the cause is as clear as in a laboratory experiment; we will therefore give some instances of the effects of such contact-metamorphism which show sometimes a change chiefly structural, while at other times changes due to greater chemical action, such as the production of new minerals, have been effected.

It is on evidence of this description, together with that of distinctive mineral composition and of the disturbances of the strata which usually accompany their presence, that certain rocks, intruded and interstratified amongst the sedimentary strata of various geological periods, are assumed to have been at one time in the hot and molten state of lava. The lithological characters and chemical composition of these igneous rocks have been given in Chapter III.

Effects of Basaltic Intrusions. In the north of Ireland the Chalk underlying the basalt is changed into a compact indurated rock like a white limestone; and when in contact with the intrusive dykes it is further changed, for a distance of 8 to 10 feet, into a crystalline marble—large-grained and dark-brown at the point of contact,—next saccharoid,—and then finer-grained, and graduating into the ordinary hard chalk, as shown in the annexed ground-plan, Fig. 203.

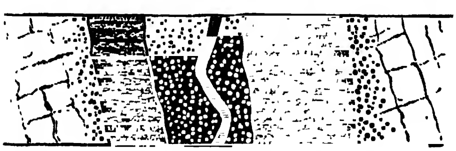

FIG. 204. *Basaltic dykes passing through Chalk; on the Shore, Co. Antrim.* (Conybeare and Buckland.)

At Portrush a dark calcareous clay or marl belonging to the Lias is converted into a hard, splintery hornstone, to a distance of from 4 to 8 feet from the basalt.

The influence of the numerous trap and basaltic dykes of Western Scotland is exhibited generally in the disturbance of the strata, induration of the sandstones, the conversion of the shales into a sort of lydian stone, and of the ordinary limestone into a splintery and granular rock; but Macculloch has shown that there are some remarkable exceptions to this rule, as in

the following instance, in which large dykes traverse sandstones without disturbing or contorting the beds, and apparently without materially altering the texture of the rocks.

FIG. 205. *Undisturbed Sandstones intersected by Trap dykes; Cliffs, eastern side of Strathaird, Skye.* (Macculloch.)

On the other hand, the great basaltic dykes traversing the Carboniferous rocks of the North of England exhibit in a remarkable manner the thermal effects produced by such eruptive rocks on the adjacent strata. Although, like those above, they sometimes produce no change of level, at other times the change has been considerable, while they have generally produced great alteration of structure. The adjacent coal is usually converted into coke, which, in one case, was found to extend for a distance of 18 feet on one side of the dyke, and of 9 feet on the other; occasionally the coal in contact is changed into sooty matter. The iron-pyrites is, as it were, roasted, and has lost its sulphur. The shales are converted into a flinty stone, and the sandstones are indurated. When limestones are traversed, they are rendered crystalline, and unfit for making lime, for a distance sometimes of 20 feet.

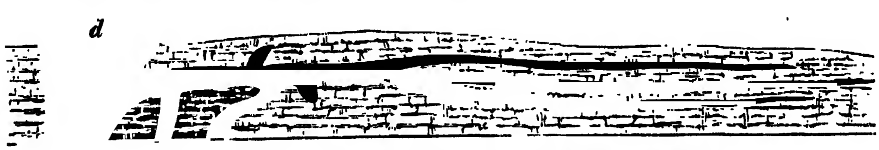

FIG. 206. *Trap intrusions; Coast of Trotternish, Skye.* (Macculloch.)

At other times the intrusion takes the form of great horizontal veins or sheets which might be mistaken for inter-stratified beds but for other collateral evidence. A case frequently quoted is the one described on the coast of Skye by Macculloch, in which the cliffs of Old Red Sandstone, 300 to 400 ft. high, are traversed by a huge dyke of basalt, *d*, that sends out a horizontal vein which afterwards divides into three tongues, and extends for a distance of 3 to 4 miles[1].

The remarkable Whin-sill of Northumberland was considered by Sedgwick[2] to be a *tabular* mass of basalt injected *horizontally* between

[1] Macculloch's 'Western Islands,' Plates xvi. and xvii.

[2] 'Cambridge Phil. Trans.,' vol. ii. p. 174, 1823.

Carboniferous strata after their deposition and consolidation,—an opinion recently confirmed by the observations of Messrs. Topley and Lebour[1]. The intrusive basalt extends for a distance of some eighty miles from east to west, with a variable width of a few miles, and attains sometimes a thickness of above 100 feet. It follows generally the planes of bedding, but occasionally passes out and traverses the strata to different levels, and in places breaks through to the surface, forming detached mounds of basalt. It has everywhere altered and disturbed the rocks in contact; but the alteration of the overlying is on the whole less than that of the underlying rocks.

The adjoining shaly beds have been converted into hard and splintery substances, resembling hornstone, or into porcelain-jasper; some of the calcareous beds have even been fused into a white glassy substance at the point of contact, and in other places vapour-cavities have been formed, some of which contain a green mineral; elsewhere at the point of contact small garnets had been formed. Notwithstanding this change, Sedgwick found that there were impressions of a common coral still remaining in parts of the rocks so affected. The limestones both above and below the basalt are rendered granular.

In a pit on the Wear, where the Whin-sill lies at the depth of 400 feet and is 20 feet thick, it overlies a thin seam of coal, which is greatly charred and deficient in volatile products. Another seam, 17 feet deeper, has but a small amount of volatile constituents left, and a third seam of coal, 52 feet below the basalt, still shows a perceptible difference from its ordinary characters elsewhere. The surrounding strata have, on the other hand, had some effect on the intrusive basalt[2].

The old trap-dykes of Ashburton and Bickington and other parts of Devonshire, which cut through Devonian limestones, have, according to Mr. Godwin-Austen, dolomitised them to some distance from the point of junction. The same dykes have converted the slates at Holbeam into a compact flinty mass. At Penwood the Carboniferous shales have been changed into jasper-rock; elsewhere the limestones have been crystallised to a considerable distance from the dykes; slates have lost their colour, and are either porous, or baked and splintery; and the Red Sandstone has been hardened and its lines of stratification obliterated[3].

The volcanic rock intruded amongst the Carboniferous Limestone and the Lias in the railway-cutting at Bleadon-hill, Somerset, has altered the limestone to a distance of from five to twenty-five feet from the points of contact. It first loses its blue tint, and becomes brittle, at the same time passing to light-red, then successively to buff, bright deep-yellow, and

[1] 'Quart. Journ. Geol. Soc.,' vol. xxxiii. p. 406, 1877.
[2] L. Lowthian Bell in 'Proc. Roy. Soc.' for 1875, p. 543.
[3] 'Trans. Geol. Soc.,' vol. vi. pp. 471–476.

deep-red. In the two latter stages it is crystallised into obtuse rhomboids, like calcareous spar, into which it finally passes [1].

At New Cumnock in Ayrshire, a seam of coal on approaching a basaltic dyke passes into anthracite, and then into an impure graphite. In the Durham coal-fields, the coal, in one instance, is altered to a distance of above 100 feet from the dyke, and part of it passes into a sooty mass; and in New Jersey a sandstone is said to show alteration to a distance of a quarter of a mile from the igneous rock; but these are extreme cases. At Meissner (p. 390) the effects of the great capping of basalt on the underlying lignite series, which is as much as 100 feet thick, extends to a depth of 18 feet. An upper thin seam of carbonaceous clay is calcined; the lignite in contact is first converted into an anthracite with a metallic lustre, and then into a bright coal and a sort of vitreous jet, which pass down into valueless earthy lignites.

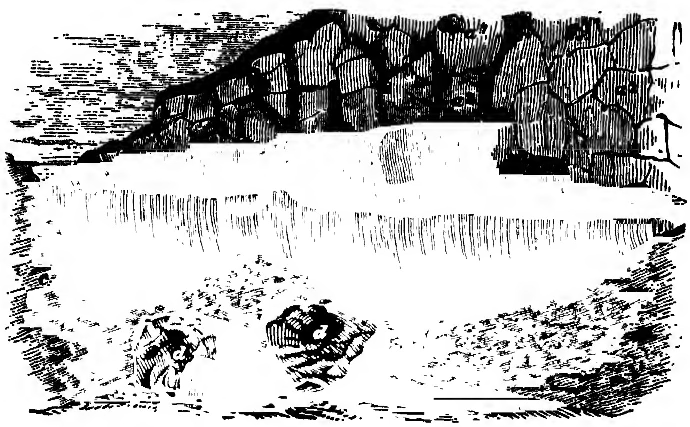

FIG. 207. *Section of an altered Clay-bed under Toadstone in Tideswell Dale.* (J. M. Mello.)
a^1 and a^2, Compact Toadstone, and a^3, Amygdaloidal and vesicular Toadstone,—together 12 feet. *b.* Prismatic red clay, 9 feet. *c.* Clay and limestone débris. *d.* Limestone blocks.

Some deep-seated shales in the proximity of an intrusive mass of igneous rock, in one of the coal-mines of Coalbrook Dale, are hardened and bleached, and the ironstone has burnt of a brick-red colour, but the effect did not extend far. Red sandstones in contact with dykes are often bleached and whitened, owing to changes in the colouring iron-peroxide, and the subsequent action of water. At other times, on the contrary, the iron in the igneous rock has stained the encasing rocks. Clays and sandstones are often rendered columnar. A good example of this, resulting from the contact of one of the Toadstones with a bed of clay in the Carboniferous series of Derbyshire, is shown in the above section [2].

[1] Williams, 'Quart. Journ. Geological Society,' vol. i. p. 47.
[2] Mello, Ibid., vol. xxvi. p. 702.

Another well-known case is that of the Quadersandstein of Saxony, which, in the proximity of basaltic rocks, becomes greatly hardened and finely columnar.

Italian Mountain in the Elk Range of Colorado is a striking instance of a mountain peak literally filled with dykes. The strata are highly metamorphosed, and consist of quartzites, altered limestones, and sandstones of Carboniferous age (tilted at high angles by protrusive granitic and trachytic rocks), through which igneous rocks have been pushed in the form of dykes. The jointing of the trachyte is so regular that it gives it the appearance of a stratified rock.

FIG. 208. *Summit of Italian Mountain, Colorado, 13,255 feet.* (Hayden's Report for 1873.)

Greenstone Intrusions. We have already noticed the annexed (Fig. 209) instructive section in North Wales[1]. A bed of greenstone (diorite) has intruded through slates of Lower Silurian age, which it has porcelanised, rendered flaky, and speckled both above and below like the so-called 'snake-stones;' while some of the slaty fragments caught up in the igneous rock have the appearance of a felspathic trap. The slates are cleaved, but the cleavage does not affect the altered portion of the rock.

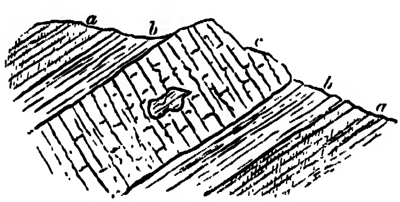

FIG. 209. *Section of Diorite* (*c*) intrusive through Slates; (*b.* altered; *a.* unaltered), *Ffestiniog* (Ramsay).

Great changes have been effected by some greenstones and porphyries on the black fucoidal shales (Cambrian?) near Christiania[2]. They first pass into greenish micaceous schists, which become gradually more and more crystalline, until as they approach the intrusive rocks, they might be mistaken for an old azoic gneiss with chlorite. This change is attributed in great part to the potash (due originally to fucoids) present in the shales.

Resulting Minerals in Sedimentary Strata. A very full account of the results of contact-metamorphism has been given by the

[1] Ramsay, 'Geology of North Wales,' 2nd edition, p. 125.
[2] Murchison, 'Quart. Journ. Geol. Soc.,' vol. i. p. 474.

late M. Delesse [1]. He found that, although the effect of the volcanic rocks on limestones has generally been to transform them into a granular marble, and often to destroy the fossils, yet at some places no alteration is caused by contact with dykes. Amongst many other instances he mentions that some fragments of a fossiliferous Muschelkalk at Kirschberg, imbedded in basalt, though bleached and rendered crystalline, retain traces of their fossils,—the unaltered rock having a specific gravity of 2.665, and the altered of 2.448. Limestones, he considered, are more apt to lose than to gain magnesia by contact.

Among the minerals commonly developed in limestones by contact with the igneous rocks are [2]—

Pyroxene,	*Garnet,*	*Idocrase,*
Gehlenite,	*Epidote,*	*Various Zeolites.*

And when the action has been very energetic, other minerals are introduced, including—

Quartz,	*Galena,*	*Sulphate of Barytes,*
Carbonate of Iron,	*Blende,*	.. *Strontian.*
Oligiste Iron,	*Pyrites.*	

Amongst the scoriæ of the old crater of Kaiserthal there was a small block of limestone which had become laminated and contained crystals of titaniferous iron, iron-pyrites, magnesia-mica, perowskite, pyrochlore, crystallised quartz, and innumerable circular crystals of apatite.

Sandstones are in general little affected. Some of the red sandstones of the Vosges have lost their colour; and some sandstones are indurated and rendered prismatic in a direction perpendicular to the dyke. Quartz pebbles imbedded in trap-rocks are unaltered.

Argillaceous strata, which often contain alkalies and alkaline earths, are generally altered into jasper and porcelanite. Some of the same minerals are found as in limestone, while hydrated oxides of iron and manganese, calcite and arragonite, are also met with.

Action on Crystalline Rocks. The effect of dykes of igneous rocks on metamorphic or plutonic rocks is very small. Dykes of large size traverse the granite of Newry without causing any change. The diorite dykes of the Vosges exercise no effects on the syenite through which they pass. The basalt of Bolin scarcely affects the gneiss it traverses. In Auvergne, however, the basalt slightly alters the granite; and at St. Brisson (Vosges) an immense dyke of diorite which traverses the granite has converted it at the line of contact into a greyish black petrosilex with mica. The fragments of granite and similar rocks, often caught up and in imbedded volcanic rocks, have suffered greater change.

[1] 'Annales des Mines,' 5th series, vol. xii. In vol. xiii. the action of the surrounding strata on the intrusive rocks is described.

[2] The number and variety depend necessarily upon the lesser or greater impurity of the limestone.

In Auvergne, fragments of granite, gneiss, and porphyry are sometimes calcined or vitrified on the surface, leaving the quartz unaltered; at other times the more fusible minerals have disappeared; and in places the fragments have melted, and a nodule only remains. At the island of Jan-Mayen the lava encloses fragments of granite, which are almost entirely melted [1]; in some fragments which have resisted more, the mica is recognisable. The trachytic rocks of Colorado, which lie over granite, enclose fragments of the latter in a semi-fused state.

General Results. Thus among the effects connected with the changes caused by the contact of volcanic and trappean rocks with sedimentary strata, is the calcining of some and the induration of others of these strata, the alteration of the coals and lignites, the contraction of sandstones and clays, the formation of some and the anhydration of other minerals,—all these changes being directly due to extreme heat. But owing to the variable conductivity of the strata, the presence of more or less water, and also to the fact that where the igneous rock has welled out slowly it might, as in the case of ordinary lava-streams, have become coated by a chilled crust, which would act as a cool pad and protect the encasing strata. Consequently, the metamorphic action resulting from the juxtaposition of these rocks varies extremely, sometimes not extending more than a few inches from the igneous rock itself, more commonly limited to a distance of from ten to thirty feet, only occasionally reaching to 100 feet, and rarely going beyond 200 feet.

Contact-Metamorphism—in connection with the so-called Plutonic rocks. In this case the effects of metamorphism extend to much greater distances from the intrusive rocks, and partake more of the character of normal metamorphism, by which no doubt they have often been partially influenced. This may be due to the circumstance of the greater depth, and generally of the greater bulk of the intrusive rocks; so that the strata affected have been subjected to metamorphic action, not only under greater pressure, but also for much longer periods of time—conditions favourable alike for more extended effects, and for the development of greater chemical action. The subject is one of extreme geological interest, and from the circumstance that the granitic tracts of Cornwall, Devon, and many parts of Europe are, like the coal districts, largely explored for mining purposes, great facilities are in these cases afforded for exact investigation and observation.

The Action of Granite. De la Beche[2] states that in Cornwall, where the slates approach the granite, they pass into mica-slate and even into

[1] Granite heated to the temperature of melted glass undergoes the same changes as it does in lava.
[2] 'Report on Cornwall and Devon,' pp. 267–269, 1839.

gneissoid rocks: and that around the granite of Dartmoor, the Carboniferous grits take the character of quartz-rocks, the slates change in appearance and are rendered flinty, and a fine clay-slate which skirts the moor becomes felspathic and striped; while certain greenstone rocks are rendered more largely crystalline, and the hornblende puts on a resemblance to hypersthene. The later microscopical examination of these Cornish rocks by Mr. Allport[1] has traced these changes further. He finds that where the granite is seen to penetrate in veins into the surrounding slates, the clay-slates gradually become more indurated, and are traversed in all directions by quartz-veins: they also become more or less micaceous; schorl begins to make its appearance, and at the junction their slaty character is in many cases completely obliterated, and they pass into a crystalline foliated rock. In some instances there is a tendency to a segregation of the quartz and mica, resulting in a sort of concretionary and spotted schist. Mr. Allport shows also that the alteration of the slates in contact with the granites has caused minute particles of ordinary clay-slate to be replaced by crystalline quartz, tourmaline, and three varieties of mica, to which tremolite, magnetite, and felspar are occasionally added.

Mr. Warington Smyth describes a remarkable case of metamorphism on the northern side of Dartmoor. The Lower Carboniferous shales, which are there in contact with the granite, are converted, along a band nearly 100 feet wide, into garnet-rock; and this is succeeded by another band, above 300 feet wide, consisting of alternations of the same rock with hard schists containing copper; and he informs me that he has since found in these beds not only wolfram, but also the rarer tungstate of lime. He considers it easy to account for the presence of garnet (together with actinolite and axinite),—the materials needful for their formation being contained in the original sediments, and becoming defined and crystalline under the influence of the granite,—but he finds it more difficult to account for the copper- and tungsten-ores, as they must have been derived from other sources—possibly from some neighbouring metallic vein[2].

The great slaty masses of rock flanking the granitic ranges of the Highlands of Scotland may belong to normal rather than to contact metamorphism. Among the products of change may be noticed the frequent formation of crystals of iron-pyrites in the metamorphic slates, and the conversion of calcareous bands into a finely granular marble. These rocks will be found described by Macculloch and other geologists.

Degree of Heat. Murchison has described the effects produced on some Lower-Silurian strata containing *Pentamerus oblongus* to the north of Drammen in Norway. A large-grained reddish granite there protrudes

[1] 'Quart. Journ. Geol. Soc.,' vol. xxxii. p. 407, 1876.
[2] 'Trans. Roy. Geol. Soc. Cornwall,' vol. ix. p. 43, 1875.

through, and is injected into, a dark-coloured limestone, which is altered to a considerable distance from the line of junction. The limestone is converted into a crystalline marble, worked in extensive quarries 40 to 50 feet deep, the strata being sometimes welded together, as it were, and with few or no traces of bedding or of fossils. As this rock approaches the granite, it becomes farther changed, crystals of garnet appear, and it finally assumes the aspect of a compact garnet-rock [1]. At Mount Konnerud near Christiania, the Silurian shales, for a width of 225 feet, are converted into grey, green, brown, or white crystalline schists, which near the granite pass into garnet, epidote, and gneissic rocks, while concretions in the shales are converted into nodules of brown garnet [2].

In the Vosges, on the contrary, although the limestone in contact with the granite is converted into marble, the effect does not extend far. In Saxony, where a granite overlies a Cretaceous limestone, it has produced hardly any alteration; and in Elba fragments of limestone, imbedded in granite, also of Tertiary age, are merely hardened without losing the traces of its fossils. In the Pyrenees some blocks of limestone in granite, about one foot thick, although calcined and white externally, still retain their original bluish colour in the interior [3]. In New Jersey, however, a siliceous limestone is altered to the distance of fifty feet.

Coal in contact with granite is converted into anthracite or graphite, but never into coke as when in contact with volcanic and trappean rocks. On the other hand, some minerals common in connection in the latter rocks and in the strata in contact with them, are wanting in the granites and associated strata.

The smaller veins of granite constantly traverse sedimentary rocks without causing any alteration in their structure.

Notwithstanding the apparent absence of the higher temperature that accompanied the molten traps and lavas, metamorphism has often extended to considerable distances from the disturbing granite. In the neighbourhood of Christiania this zone has an average width of about 1200 feet. In the Pyrenees it extends to about a mile, and in a few rarer instances the effects are perceptible to a distance of two miles [4]. Such cases may be, however, attributable as much to regional or to normal metamorphism as to contact metamorphism. The distance to which the surrounding rocks have been affected depends, of course, on the magnitude of the mass of granite, and the action of a low heat long prolonged. A moderate degree of heat, combined with pressure and moisture, is sufficient to convert an earthy limestone into a crystalline marble. The very infusible

[1] 'Quart. Journ. Geol. Soc.,' vol. i. p. 473, 1845.

[2] Credner's 'Géologie,' French edition, p. 292.

[3] Delesse, *op. cit.*, p. 723.

[4] Daubrée, 'Sur le Métamorphisme,' p. 65, 1860.

simple silicates of alumina, such as *chiastolite*, *disthene*, *staurolite*, etc., so common in metamorphosed argillaceous strata in proximity to granite, must have been formed, under the influence of a low heat, by molecular action alone; for the rocks have in no instance been fused, and often retain impressions of their fossils. Many years ago M. Bobblaye drew attention to the ampelites (black slates) of Salles de Rohan, which, though they pass into schists with large crystals of *chiastolite*, continue to exhibit impressions of *Orthis*, *Trilobites*, and other fossils of Lower-Silurian age[1].

Murchison found that, although the unaltered Silurian strata of central Russia pass on the flanks of the granitic axis of the Ural Mountains into crystalline limestones, their encrinital remains are preserved[2]. M. Daubrée mentions that at Rothau in the Vosges there is an intrusion of a great mass of syenitic-granite among Devonian strata, by which the latter are, for a distance of several hundred yards, entirely modified. In places the rock consists only of lamellar pyroxene, epidote, compact garnet, and other such minerals with specks of galena. In the midst of this rock, entirely formed of silicates of this description, he discovered perfectly well-preserved impressions of corals (especially the *Calamopora* (*Alveolites*) *spongites*, Goldf.) and of polyzoa. Cavities in the fossils, caused by the partial removal of the carbonate of lime, were lined with crystals of the same minerals, amongst which the most abundant were long crystals of hornblende, often penetrating crystals of quartz. Green garnets were found in the same geodes; and crystals of axinite of considerable size were, for the first time, recognised[3].

Amongst other minerals associated with granite, and found in the metamorphic rocks in contact with it, are *tourmaline*, *zircon*, *fluor-spar*, *dipyre*, *graphite*, *spinelle*, *cassiterite*, *felspars*, *apatite*, *columbite*, etc.

Contact with Syenite. The contact with syenite presents analogous effects. Ramsay mentions that near Ffestiniog in North Wales there is a boss of this rock 2½ miles long by 1 mile broad, along the flanks of which the Arenig slates are transformed into bluish-grey spotted rock, like hone-stone or variolite. This passes into a rock composed of felspathic matter speckled with hornblende (?) arranged somewhat as in gneiss, but not a true gneiss. The two rocks seem to pass into one another.

The high syenitic range south of Comrie in Perthshire exhibits some noticeable features. Veins of considerable extent run from the central mass into the adjacent slates, while smaller veins ramify in various directions. It does not seem to have produced much change in the position of the slate, but it has materially altered its mineral character. As it approaches the syenite it becomes harder and more crystalline; thin

[1] 'Bull. Soc. Géol. de France,' vol. x. p 227.
[2] 'Russia in Europe,' vol. i. p. 420.
[3] 'Géologie Expérimentale,' p. 141.

lenticular masses of red felspar and quartz, like a binary gneiss, and more or less continuous, become intermixed with layers of the blue slate, until the whole rock passes into a fine-grained gneiss. Even the coarser greywackes are greatly altered in aspect[1].

Regional Metamorphism[2]. This term has been used as synonymous with that of *normal metamorphism*, whether employed to denote the changes caused by the heat due to depth on the supposition of the existence of a heated nucleus, or evolved by mechanical work. But I consider it would be better to separate the two terms, confining the term 'normal metamorphism' to the changes due to central heat, and applying the term *regional metamorphism* to those changes effected by the agency of the physical causes to which Mr. Mallet referred the fusion of the volcanic rocks, namely, *the heat produced locally within the crust of the earth by transformation into heat of the mechanical work of compression, or of crushing of portions of that crust*[3].

This source of heat had not been altogether overlooked by geologists, though only occasionally referred to as a secondary cause; but its actual importance was not realised until Mallet investigated the subject experimentally and mathematically. As before said (p. 210) he failed to show sufficient cause for the fusion of the volcanic rocks, and his estimates may be questioned; he nevertheless satisfactorily demonstrated the enormous heat-producing power that certain earth-movements might have. This power, inadequate though it may be to explain the phenomena of vulcanicity, is singularly applicable in explanation of some of the metamorphic phenomena exhibited in mountain-ranges; and it is to be regretted that this branch of the enquiry was not followed up by the distinguished author of the interesting paper here referred to. The object of his experiments having been to establish the maximum results to be attained by the force of compression, these results bear only indirectly on the collateral problem we are here considering.

In the case of contact- and normal-metamorphism, we have—in the molten rocks and underground temperature—approximate thermal scales; but in the case of regional metamorphism the conditions are so complex, that the ordinary observations and experiments of the laboratory fail to furnish any such comparatively definite measures, and we have to look to other evidence.

Effects of Rock-Crushing. The primary object of Mr. Mallet's experiments was to ascertain the force required to crush portions of various

[1] J. Nicol, 'Quart. Journ. Geol. Soc.,' vol. xix. p. 192, 1863.

[2] See on this subject chap. iv. p. 446 of M. Daubrée's 'Géologie Expérimentale,' and a paper by the author in the 'Proc. Roy. Soc.' for June, 1885.

[3] 'Phil. Trans.,' vol. clxiii. p. 147, 1873.

rocks of given size, and to determine the quantity of heat evolved by the process. For this purpose he had cubes prepared of from 3 to $3\frac{1}{2}$ cubic inches in volume. These were subjected to the steady increase of a load until crushing occurred. The crushing weight was noted, and the heat that should be evolved calculated. The work done was then measured by the portion of a cubic foot of water at 32° Fahr. that could be converted into steam of one atmosphere (or at 212° Fahr.) by the *estimated* heat evolved by the crushing of 1 cubic foot of each class of rock. The following is an abstract of some portion of the mean results obtained in this way.

Class of Rock.	Specific gravity. Water = 1000.	Weight per square inch, at first yielding.	Mean actual pressure, at which cubes of each sort were completely crushed.	Temperature of 1 cubic foot of rock, due to work of crushing.	Number of pounds of water at 32° evaporated into steam at 212°.
		lbs.	lbs.	°Fahr.[1]	lbs.
Caen Oolite	2·337	1,620	4,966	8°	0·288
Magnesian Limestone ...	2·571	3,699	16,333	26°	0·9
Coal-measure Sandstone	2·478	10,970	29,783	86°	2·5
Devonshire Marble ...	2·717	11,708	34,938	114°	3·44
Bangor Slate	2·859	15,510	41,590	144°	4·51
Aberdeen grey Granite	2·678	16,868	51,123	155°	4·44
Inverary Porphyry ...	2·594	26,149	69,786	198°	5·22
Rowley Ragstone ...	2·827	24,039	63,737	213°	6.86

The crushing weight in the case of the specimens of the sedimentary strata was found to vary, in round numbers, from about 2 to 18 tons per square inch, while for the crystalline and igneous rocks it reached to over 30 tons (each class of rock showing considerable variations): and the mean quantity of water supposed to be evaporated by the crushing of 1 cubic foot of an average sedimentary rock was estimated to =0·03753, and of an average crystalline rock to =0·078757 cubic foot of water.

These calculations of Mr. Mallet are open to the objection that the heat was not measured experimentally, but calculated on estimates based on the crushing power. This may invalidate the exactness of his quantities, but it does not affect the truth of his general conclusions, and their applicability to the purposes of our reasoning, for which object it is sufficient at present to know that pressure and deformation are accompanied by the development of a great amount of heat. That iron becomes red hot under continued hammering, and that lead and other metals under crushing and rolling may acquire a temperature of 700° Fahr. or more, are well known facts. Experiments on rocks are however wanting, with the exception of those made by M. Daubrée, who by manipulating masses of clay in a powerful crushing machine, found that at the end of 25 minutes, the clay which at the commencement had a temperature of 18° C. was raised to 36·3° C., and

[1] Omitting fractions of a degree.

at the expiration of 45 minutes to 40·1°C.; and it was also observed that the more rigid the clay the greater was the heat evolved. He found also that a block of marble placed on a lapidary's wheel, and subjected to slight pressure whilst the wheel revolved, had its temperature raised 4·5° C. at the end of one minute.

In a similar way in Mallet's experiments, the heat produced in the metal surroundings by the complete crushing of the harder rocks was easily perceptible by the hand, and was so great with the granites and porphyries as to necessitate a delay for the apparatus to cool. Theoretically Mr. Mallet and Professor Rankine both agreed that 'in the crushing of a rigid material such as rock, *almost the entire* mechanical work (with the exception of a small residue of external work) reappears as heat.' It was further shown that, even in the most rigid bodies, crushing begins by compression and yielding, and that at this stage heat begins to be evolved.

Mr. Mallet, applying these results to the deformations caused in the earth's crust by the contraction of the cooling nucleus, observes that the compression will be greatest along lines of fault and mountain-upheavals,—so that the chief amount of the work of compression will be transferred to those lines of fracture or weakness, and the increase of temperature produced by the greater part of the internal work will cause the parts of the crust about those lines to become much hotter than the intervening parts, where the crust is undisturbed [1].

Consequently as the work thus developed is transformed into heat, that heat will be greatest along those lines or planes at places where the movement and pressure, together constituting the work, is greatest. Whence Mallet concluded that along or about such axial lines of concentrated compressive and crushing work the temperature may locally rise to a red heat, or even to that of fusing the rocky materials crushed and of the pressing-together-walls themselves adjacent to them. This was, in his opinion, the real nature and origin of the volcanic heat as now produced on the globe.

Heating of Rocks in disturbed Areas. Although the hypothesis fails, for reasons before assigned, in its application to vulcanicity,—especially from the fact that the great lines of disturbances and compression of the Alps, Pyrenees, and other mountain-chains are free from either active or extinct volcanoes,—there is nevertheless reason to believe that this source of heat may have been adequate to produce great molecular changes in the rocks along the lines of disturbance and upheaval. It is precisely along such lines that not only are the older rocks metamorphosed, but rocks of Cretaceous and Tertiary age, which usually have not been affected by normal metamorphism,—coming in these mountain-

[1] *Op. cit.*, pp. 165 and 167.

chains under the influence of the disturbing forces,—have undergone a change analogous to that produced by normal metamorphism.

If the disturbances had taken place at once, or suddenly, and the rocks had been wholly crushed, the calculations of Mr. Mallet were more likely to have been borne out. But the movements were, in all probability, for very long periods of extreme slowness, and it was only when the tension had reached a certain point that disruption took place, and the movement of the parts became more rapid, pending the restoration of a state of equilibrium; nor is there any reason to suppose that the rocks were at any time crushed in the complete manner accomplished experimentally by Mr. Mallet. Consequently much of the heat developed would be dissipated during the long slow compression, and the maximum effects indicated by the experiments would not obtain in nature. Still, as these experiments show that the weight at which the first yielding of the rock takes place is not more than one-third of the crushing weight, the thermal effects might still be considerable, provided the time the heat had to spread through the adjacent rocks were not excessive. It is also certain that greater and more concentrated effects would result at the time of actual disruption and faulting. The gigantic foldings of the rocks in the Alps (Pl. p. 304), and the magnitude of the faults there and in the Pyrenees, show how immeasurably great the forces then in operation were, and indicate how important must have been the consequent conversion of even a portion of these forces into heat.

Objections have been, in some instances, raised to the sufficiency of normal metamorphism to explain alterations of the sedimentary strata in mountain-chains, on the grounds that unaltered strata alternate with altered strata. This alternation may be sometimes explained by inversion of the strata; or, where that does not exist, it may be due to the circumstance that differences of mineral composition, or in the proportion of the water of imbibition, have caused the metamorphism to affect different beds in different degrees. On the theory of *regional metamorphism*, another explanation suggests itself by the way in which differences in the resistance of the rocks develop different quantities of heat. Mr. Mallet has shown by experiments on the compressibility of rocks at Holyhead, that, although certain quartz and certain slate-rocks were compressed by precisely the same force before their elastic limits were passed, yet, owing to differences in their compressibility, the heat developed in the rocks when released would, on his calculation, render the quartz-rock nearly three times as hot as the slate-rock. In this manner, therefore, it seems possible to account for this special metamorphism of the strata in mountain-chains, and for its frequently localised occurrence.

Examples at different Times. Among the many examples of the metamorphism of the newer geological strata may be instanced that

of the Lower Cretaceous strata on the flanks of the Pyrenees. They are there represented by dark schists and crystalline limestones, while at a short distance from that range they consist of marls and ordinary limestones. In the Alps, strata of Middle Eocene age are, at the Diablerets, converted into hard black slates, which are purely local; while the soft and earthy calcareous Nummulitic strata of the south of France are represented in the Alps by massive limestones and crystalline marbles. Normal metamorphism cannot here be invoked, because it does not appear that these rocks have ever been covered by any great thickness of newer rocks, or depressed to such depths so as to bring them within the influence of the higher underground temperatures. At the same time, contact-metamorphism may, in some cases, where there is a central axis of granitic rocks, as in parts of the Alps and Pyrenees, have shared in producing the actual results; but in places where there are no eruptive rocks, the effect may possibly be better explained by the action of *regional metamorphism.*

The remarkable changes which take place in the condition of the coal of Pennsylvania, as it ranges to the Appalachian Mountains, must be referred to regional rather than to normal metamorphism. This mountain-range consists of a series of great parallel folds, increasing in acuteness as the central axis is approached. Eruptive rocks are absent; but nevertheless the strata, as they range towards the central chain, become more crystalline, and the coal, which at a distance is ordinary bituminous coal, passes into anthracite, and even graphite. The late Professor H. D. Rogers divided this great coal-field into four basins. The coal in the less disturbed district near the Ohio River, where the flexures are extremely gentle and wide apart, contains from 40 to 50 per cent. of volatile matter; in the wide basin further east it decreases to 30 or 35 per cent.; in the basins of the Alleghany range, in which although there are no important dislocations or great flexures, there are some extensive and symmetrical anticlinal folds of the flatter form, the proportion of the volatile matter in the coal varies from 16 to 22 per cent.; while in the most easterly chain of basins, which are associated with the boldest flexures and greatest dislocations, with close plications, vast compression, and inversions of the strata, the quantity of volatile matter in the coal is reduced so low as from 6 to 14 per cent.

A somewhat analogous instance is presented by the Carboniferous series of Belgium. The excessive squeezing, faulting, and inversion which the Coal-measures have undergone on the flanks of the axis of the Ardennes (Sect. 2, p. 260) is there accompanied by an alteration, in places, of the highly bituminous coals into dry coals and into anthracite; while the Carboniferous and Devonian limestones amidst the sharply convoluted and folded strata of the Ardennes are there, as they are also on the line of the same disturbance in the Boulonnais, transformed very commonly into crystalline

marbles. The few exposures of eruptive rocks are all on a small scale, and affect the adjacent rocks only by contact metamorphism. It is probable that the anthracite of South Wales is the result of similar regional metamorphism.

This alteration of coal forms a convenient test of the temperature under which 'regional metamorphism' may have been effected; for, while it requires a red heat to convert coal into coke, its conversion into anthracite is effected in presence of moisture at much lower temperatures; and, as already mentioned, M. Daubrée has even converted wood, by exposure for some time in water under pressure to a temperature of 300°C. (572° Fahr.), into an anthracite so hard as scarcely to be touched by steel, and so infusible as to burn with extreme slowness even in the oxidising flame of the blowpipe, while at the same time it is rendered, like the diamond, a non-conductor of electricity.

Residual Heat. Nor is it impossible that in the newer mountain-chains of the world, some residual portion of the heat thus mechanically evolved may still exist and cause certain aberrations in the position of the underground isothermal lines. The elaborate series of observations made by Dr. Stapff in the St.-Gothard Tunnel gives support to this view. From his corrected reductions, it would seem that the rate of increase of temperature with depth at the north end of the tunnel, where it passes through gneiss and granite, exceeded the normal rate for the whole tunnel by several degrees, and that for this there was no obvious explanation. As however this part of the tunnel passes through rocks which have been disturbed and compressed at a late geological period, it is not impossible that we may there have some of the heat then evolved still remaining in the rocks.

It may also be possible that this cause has some connection with the thermal springs so common in certain mountain-chains. Some of these springs are, no doubt, due to the presence of eruptive rocks; but in many cases there are none of these rocks in the neighbourhood, and yet hot springs are common. Others may, of course, be due to the depth of the source; but their numbers and their position often militate against this view. In the Alps they are not infrequent, and sometimes occur at very high levels. In the Pyrenees the number of thermal springs exceeds 150; and Professor W. B. Rogers states that there are 56 such springs in the Appalachian chain of mountains. Seven of these are on lines of fault or inversion: the others issue on lines of anticlinal axes or at points near to them.

Normal Metamorphism. But besides the changes that contact and regional metamorphism have produced in the structure and mineral composition of certain strata, there is the larger and more common class of metamorphosed rocks, that have evidently been affected by a more general cause. There are extensive tracts of schistose, gneissic, and other

crystalline rocks, free from intrusive rocks and distant from mountain-chains, which nevertheless are supposed, from their bedded structure and from other points of analogy, to be metamorphosed sedimentary strata altered by thermal and chemical action under certain other conditions to which they have in common been formerly subjected. Geologists have, therefore, had in this case to seek for a more wide-spread and general cause, and that cause is found in the heat derived from the nucleus of the globe, or internal heat.

Temperature at Depths. It having been determined that the underground temperature increases at the rate of 1° Fahr. for about every 45 to 50 feet of depth, and there being reason to suppose that this rate of increase continues, within moderate limits of probable variation, to depths beyond the reach of observation, it follows that at a certain depth the temperature of boiling water (at the atmospheric pressure) would be reached, and at a greater depth, that of rock-fusion. It is also tolerably certain, from the lesser or greater permeability of the strata (Chapter X), and from the capillarity of the rocks, that water finds its way to a depth greatly exceeding that at which it would be converted into steam at 212° Fahr.,—possibly to that of the critical point of water (773° Fahr.?) or more. We may thus have at certain depths, in any part of the globe, the three conditions of heat, moisture, and pressure necessary to produce the metamorphism of sedimentary strata,—the depth at which the temperature of 212° Fahr. would be reached being about 8000 feet, and that of red heat (say 1250° Fahr.) about 58,000 feet.

Even in quite recent geological times, when the earth was approaching its present state of rigidity, there were, as before shown (Chapter XIII), elevations of the land to the extent of 1000 to 2000 feet; and, if elevations of that amount, then, in all probability, there were depressions of equal amount in other areas. But in earlier geological times, with a more flexible crust and more fluid interior, movements of depression were more frequent and continuous; and that such movements did take place is certain from the fact that in Tertiary times we have in places deposits superposed successively and conformably one on the other to the thickness of 5000 feet or more, and in Palæozoic times of 20,000 feet or more. Now it is easily demonstrable that a large proportion of these several groups of strata were deposited in shallow waters, or in waters of no very great depth; consequently, as these successive groups of strata accumulated and gradually filled the sea-basin in the long course of time, equivalent slow movements of depression must have been going on to maintain throughout those geological periods the nearly uniform depth of water necessary for the continuance of sedimentation, and for the maintenance of like orders of life.

Owing to the constant transmission of heat from the interior to the surface of the earth, each of the successive deposits, as they were gradually

carried to greater depths from the surface, passed into zones of higher temperature, and became by degrees heated in proportion to the depth of depression, whether to the isotherm of 212°, or of 500°, or of 1000° or more [1]. The necessary consequence of this systematic subsidence has been to subject the earlier and deeper-seated portions of the sedimentary strata to conditions favourable to extreme metamorphism, so that, when subsequently upraised to the surface, they may re-appear as schistose and crystalline rocks, —with their structure altered, their bedding often lost, and, if they have reached a depth where the heat has been great enough, with their fossils destroyed, or may-be the rock itself fused.

Various Periods of Metamorphism. In this way, a considerable portion of the older and more deeply-seated sedimentary strata have undergone transformation, although to a very irregular extent. The Cambrian strata of Britain, and of Europe generally, are largely metamorphosed. In Anglesea the metamorphism of these rocks had even taken place before the deposition of the Lower-Silurian rocks. Whereas in the United States there are Lower-Cambrian strata (Potsdam Sandstone) which have undergone but little change, and are no more altered than most Mesozoic rocks.

The Silurian strata of Scotland are highly metamorphosed, and the change was effected before the deposition of the Old Red Sandstone, for the conglomerates of that age contain pebbles of metamorphic Silurian rocks. In Ireland the limits of metamorphism stop at the top of the Lower-Silurian; the Upper-Silurian strata being unaltered, and containing pebbles of the altered lower beds. In Wales, the limits of metamorphism vary; but it nowhere extends into the Carboniferous rocks. In Shropshire and Herefordshire the Upper-Silurian and Old Red Sandstone are unaltered; whilst in Cornwall and Devon the rocks of that age are highly metamorphosed, and the metamorphism affects, in places, the Lower Carboniferous strata. In Brittany the Lower Devonian and Silurian strata have undergone great alteration. In Central Russia, on the other hand, the Silurian strata are unaltered; and it is not until they approach the Ural mountains that they begin to show symptoms of change.

It is now well ascertained that normal metamorphism may take place without any very high temperature. Crystals of quartz and pyroxene (diopside) have been formed in superheated water at a temperature of 400° C. (752° Fahr.[2]). They are both found in mineral veins of hydrothermal origin; and they are also, as before mentioned (p. 407), met with in rocks metamorphosed by contact, where the heat was not sufficient to cause fusion, or even to destroy the fossils.

[1] See Sir John Herschel on 'Secular Variations of the Isothermal Surface of the Earth's Crust,' 'Quart. Journ. Geol. Soc.,' vol. ii. pp. 548, 596; and a paper by Babbage, Ibid., vol. iii. p. 186.

[2] Daubrée, *op. cit.*, p. 156 *et seq.*

But besides the altered rocks of known geological age, there are others where the metamorphism has been more general and intense, and where the questions of age and origin are surrounded with greater difficulties.

Schistose and Gneissic Rocks of Archæan Age. This great body of rocks attains, when fully developed, a thickness of from 20,000 to 50,000 feet or more. Whether they are of sedimentary or chemical origin, or whether they form part of disintegrated or altered fundamental rocks of pseudo-igneous origin, are still questions discussed.

It was suggested by Scrope that gneiss was at its origin a crystalline rock—that it was the outer portion of a body of viscous or plastic granite, which, as it was protruded through the overlying rocks, became compressed and drawn out along sliding planes or surfaces parallel to one another, the crystals of mica following the movement in the direction of their longer axes, and thus causing lamination and foliation.

Again, it is contended that the heat on the surface of the globe was, during the Archæan period, such that the quartz and the other constituents of these rocks were dissolved in the superheated alkaline waters which first found lodgment on the surface, and that from this superheated solution the earlier gneisses, limestones, etc., were precipitated as from a chemical solution, and that the foliation of the former was induced by the subsequent pressure of the overlaid rocks.

An objection to these views is that the great masses of Archæan gneisses of Scandinavia and North America alternate with thick beds of quartzites, crystalline limestone, hornblende-schists, and iron-oxides, indicating a definite and distinct assortment or bedding on a large scale, and showing that there was successive deposition and selection, and not merely a mechanical rearrangement of the constituent minerals of a homogeneous mass. That this Archæan gneiss is often underlain by granite is clear, from the frequency with which it is penetrated by granite veins; but it also alternates with it. It likewise wraps round the granitic *massif* of Central France, underlies the old Palæozoic rocks of Brittany, forms some of the highest ranges of the Alps and other mountain-chains, is distantly connected with the granites of Cornwall and Devon (*postea*, p. 423), and underlies the Cambrian rocks of Scotland. It is also possible, as no conglomerates nor derived fragments are found in the lowest or oldest division of the Archæan gneisses—and they are remarkably uniform in character all over the world—that the materials of which they consist may have been furnished by the decomposition of such silicates as formed the first outer solidified crust of the globe, and which were then re-formed under atmospheric influences and with the conjoint action of moisture or water.

In any case the Lower Archæan rocks must have undergone metamorphism very soon after their deposition, for the occurrence of worn fragments and pebbles derived from those older rocks in the conglomerates

that occur both in the Huronian and at the base of the Cambrian series shows that the earlier deposits already existed in the state of crystalline schists and gneisses. It is also possible, as these rocks were, anterior to Palæozoic times, strongly contorted and wrinkled, that regional metamorphism produced by the mechanical work of this crushing and folding may have supplemented the normal metamorphism, just as the regional metamorphism of mountain-chains has acted in places where it has doubtlessly been preceded by the action of an older normal metamorphism.

Atmospheric Pressure at Former Periods. If we are to adopt the hypothesis of a molten globe gradually cooling,—and no other hypothesis so well meets all the requirements of the geological problem,—we must be prepared to consider the various consequences of that hypothesis, however far they may lead us from the terrestrial conditions which now prevail. There must thus have been a period, when geological history commenced, at which the refrigeration of the surface had proceeded so far as to allow of the condensation of water on the surface. Previously to that time the whole volume of water now on the globe could only have existed in the state of vapour in an atmosphere of enormous magnitude and corresponding pressure. On the assumption of Humboldt that the mean depth of the ocean is 3500 mètres, and that this depth, if distributed equally, would form a stratum 2563 mètres thick over the whole globe, M. Daubrée has calculated that this converted into vapour corresponds to a pressure of 248 atmospheres[1]. Independent and later calculations by Mr. Mallet[2], give for the volume of water on the globe, if spread out uniformly on the surface, a depth of 1·383 mile, which converted into vapour would equal a barometric pressure of 202·74 atmospheres. Or, taking the estimate, I have before given, of a mean ocean depth of 8000 feet, the mass of water existing as vapour in the atmosphere would still give in round numbers a pressure of about 200 atmospheres.

Temperature of the early Ocean Waters. Now, as the boiling-point of water under a pressure of twenty-five atmospheres has been proved experimentally by Regnault to be 437° F., and the empirical formulæ show a nearly corresponding increase of pressure with increase of temperature, it follows that the early ocean-waters would have had a temperature even exceeding the present boiling-point of 212° F., while the reduction of the high temperature then prevailing must have been the slow work of long ages as the course of secular refrigeration proceeded.

How far the secular cooling of the globe may have proceeded at the Archæan period it is impossible to say; but that the crust of the earth was then comparatively thin, that the temperature of the surface was

[1] 'Études sur le Métamorphisme,' p. 121, 1860.
[2] 'Quart. Journ. Geological Society,' vol. xxxvi. p. 112, 1879.

high, that the atmosphere was one of great extent, and that the pressure of that atmosphere was such as to raise the boiling-point of water, there can be little doubt. The solvent power of water under these circumstances must, like that of some of the thermal waters of the present day, have been very considerable. If, however, we are to admit that vegetable growth in the form of submarine forests of fucoids, and low animal life in the form of foraminifera (Eozoon), made their appearance during the Archæan period, a very important lowering of temperature must soon have taken place. Still we do not know under what conditions of temperature these could have lived; we only know that many low forms of life can thrive in waters having a comparatively very high temperature. That the waters were saline, and that the pressure, however caused, was considerable, is indicated by the fact that liquid-inclusions, although different in size and shape to those in the quartz of granite, are common in the quartz of gneisses and mica-schists; and that those inclusions often consist of super-saturated solutions of alkaline, chlorides and sulphates. It is stated, on the authority of MM. Benecke and Cohen, that the quartz of the gneiss of Odenwald contains inclusions in which all the constituent elements of the rock are found [1].

Chemical Sediments. We cannot, however, agree with those geologists who hold that the Archæan rocks are the result of direct crystallisation from a heated menstruum. They consider that, owing to the greater thickness and pressure of the atmosphere, the heat was stronger and the solvent power of the waters was more extreme; and that, consequently, the first condensation of the atmospheric vapours produced a chemical menstruum in which the mineral substances were held in solution and furnished the crystalline elements of the gneisses; while after further cooling chemical action gave way by degrees to mechanical action and argillaceous schists in turn were deposited [2]. On the other hand, the presence of one life-form of a low type (the *Eozoon canadense*) is scarcely sufficient to assign an organic origin to the great lenticular masses of crystalline limestone associated with the Archæan gneisses. They are more probably the result of chemical reactions in waters charged with the various salts and alkalies set free by the decomposition of the silicates and resulting in the precipitation of the carbonate of lime. Dr. Sterry Hunt suggests that the lime existed in the state of chloride, which, by double decomposition with carbonate of soda, gave rise to carbonate of lime and chloride of sodium or common salt. He supposes the lime to have been derived originally from anorthite or the other lime-felspars [3].

[1] De Lapparent, 'Traité de Géologie,' p. 637.

[2] See Credner's 'Géologie,' Fr. ed., p. 299, 1879.

[3] See Sterry Hunt, on the formation of the Crystalline Rocks, 'Chemical and Geological Essays,' pp. 24, 63, 283, 302.

To what, however, are we to attribute the origin of the chlorine? May not its combination with the sodium salt have been direct instead of through the process of double decomposition? The independent presence of lime as a chloride is difficult to suppose. Chlorine could, like the other gases, and like the vapour of water, only have existed at first as part of the atmosphere. In presence of the vapour of water and light, chlorine is converted into hydrochloric acid; and this would be removed with the rainfall into the surface-waters, and there combine with any nascent alkalies and earths, lime included, set free by the decomposition of the silicates. By some reaction of this nature, it is conceivable that the chloride of sodium now in the ocean may possibly be accounted for. For the present, however, this explanation must be considered very hypothetical. Still, it is one which commends itself as a hypothesis, and conforms to the probabilities of the case.

In the same way the protoxide of iron liberated by the decomposition of the ferruginous silicates of the more basic rocks would enter into combination with the carbonic acid of the surface-waters, and might be subsequently precipitated as a hydrated peroxide. The conversion of this hydrated oxide into hæmatite, which change takes place in presence of water at a high temperature, would result as part of the general metamorphism of all the sediments of that period.

Minerals. Amongst the accessory minerals, the product of metamorphism in the Archæan gneisses and mica-schists, are *apatite*, *epidote*, *garnet*, *pyroxene*, *hornblende*, *scapolite*, *mica*, *calcite*, *serpentine*, *magnetite*, *hæmatite*, *chondrotite*, *wollastonite*, *sphene*, various *felspars*, etc.

The early gneisses pass by insensible gradations, on the one hand, into granite, and on the other into mica-schists, with which crystalline limestones, quartzites, and iron-ores are interstratified. Between the Archæan rocks and the succeeding Cambrian series there is in Europe, as well as in America, a marked break in continuity. We pass at once from rocks always crystalline, and of obscure sedimentation, to rocks distinctly stratified and derivative, and crystalline only under certain conditions of local metamorphism. It cannot, however, be doubted that passage-beds must somewhere exist; and such possibly may be the newer gneisses of Bavaria, or some of the Norwegian schists.

The range and local conditions of these Archæan rocks, and their relation to the Palæozoic series, will be more fully described in the first chapter on Stratigraphical Geology.

CHAPTER XXIII.

METAMORPHIC AND PSEUDO-IGNEOUS ROCKS.

GRANITE. ITS RELATIONS TO GNEISSIC AND SCHISTOSE ROCKS. CHEMICAL COMPOSITION OF GRANITE AND ALLIED ROCKS. ACCESSORY MINERALS. RANGE AND AGE OF GRANITE: BRITISH ISLES; FRANCE; PYRENEES; ALPS; SCANDINAVIA; GERMANY; AMERICA; INDIA; AUSTRALIA. ORIGIN OF GRANITE: WHETHER IGNEOUS OR METAMORPHIC. OBJECTIONS ON EITHER SIDE. TYPICAL MINERALS. APPARENT BEDDING. LIQUID INCLUSIONS. ROCK-PRESSURE. ATMOSPHERIC PRESSURE. ACTION OF WATER. HYDROTHERMAL FUSION OF ROCKS.

Granite. This, the most remarkable of all the crystalline rocks, has a very wide and irregular distribution, rising in bosses chiefly amidst Palæozoic strata, and in vast bands generally coincident with mountain ranges—more rarely in dykes. It was at one time very generally supposed to be a rock due entirely to igneous fusion, and of great geological antiquity, but very different views are now entertained of its age and origin. Instead of being an original igneous rock, it is a question whether it is not a rock re-formed out of other and sedimentary rocks; while it is certain that its protrusion has taken place at various geological periods, although in a ratio decreasing from Palæozoic to Tertiary times.

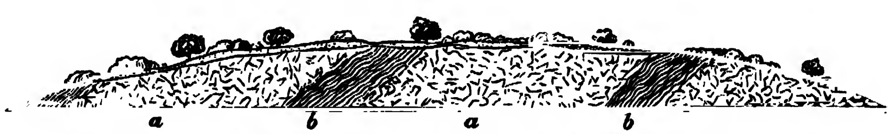

FIG. 210. *Intercalation of Gneiss* (*b*) *and Granite* (*a*) *road cutting between Vannes and Auray, Brittany.* (Huguenin.)

Its Relations to Gneiss. Both chemically and mineralogically there is little or no difference of composition between the gneissic rocks described in the last chapter and granite. They both consist of quartz, felspar, and mica, with various accessory minerals. The difference is mainly one of arrangement, the former being foliated, with the mica in alternating planes, and the latter being structureless. It is often impossible to draw the line between them; they pass apparently one into the other; and there is frequently an interstratification of granite or granitoid rock with the mass of the gneiss; but this seems to be confined to the Archæan gneisses. Fig. 210 exhibits an instance of this in the Archæan rocks of

Brittany, where it is of common occurrence. In the *massif* of the mountains of Central France, which is composed almost entirely of granite and gneiss, the latter passes up into mica-schists, and downwards into a fine-grained granite with which it often alternates. The porphyritic granite which is eruptive through the older rocks is not associated with gneiss[1]. In the mountains of the Esterel, a mass of graphic granite, 16 feet thick, is intercalated with mica-schists.

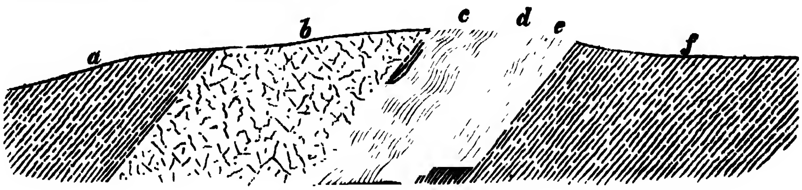

FIG. 211. *Section in the Esterel Mountains.* (Dufrénoy and Elie de Beaumont.)
a. Mica-schist. *b.* Graphic Granite bounded by seams of earthy and carbonaceous schist. *c, e.* Crumpled schists. *d.* Carbonaceous schist. *f.* Mica-schist with carbonaceous seams.

Murchison describes the azoic gneiss of Scandinavia as remarkable for the abundance of granite-veins (contemporaneous seams?) which it contains, and notes that this group of rocks, which forms a mass not less than 20,000 feet thick, is distinct and older than the eruptive granite, which in Norway has intruded into strata of Lower-Silurian age[2].

In Germany the Lower-Archæan gneisses alternate with granulite, serpentine, syenitic granite, and hornblende-schist, forming a series of rocks estimated to be about 50,000 feet thick. In some districts also the gneiss and granite alternate with beds of graphite, hälleflinta, and crystalline limestones.

In the States of America and in Canada Sterry Hunt considers that many rocks are called granite which are really granitoid gneisses intercalated amongst Laurentian schists and gneisses; but he states that in Eastern Canada there is a newer intrusive granite which breaks through strata of Devonian age and underlies Carboniferous strata[3]. On the Pacific border granites are intercalated with Archæan gneisses, showing no signs of eruptive character.

The liquid inclusions, so constant in the quartz of granite, are stated by Zirkel to abound also in the quartz of gneiss, mica-schist, and quartz-porphyry in America and in Europe[4]. The only difference that has been pointed out in these inclusions is that those of the schistose rocks are in general smaller and more elongated.

Chemical Composition. Uniform as are the mineral constituents of typical granites, their chemical composition differs considerably

[1] Elie de Beaumont, *op. cit.*, vol. i. p. 109.
[2] 'Russia in Europe,' p. 14.
[3] 'Geol. Survey of Canada for 1863,' p. 452, and 'Chemical and Geological Essay,' chap. xi, 1875.
[4] 'Microscopical Petrography,' chaps. ii. and iii.

owing to the difference in the relative proportion of the constituent minerals. The silicates, in crystallising out in definite combinations, have left a lesser or greater residuum of silica, which forms an ever variable quantity. This is a necessary consequence, if we are to consider granite, not as a rock derived from an original magma, but as reconstructed from gneisses, mica-schists, and argillaceous schists, in which the proportional mineral assortment varies so widely. Where the limits of variation required for the formation of granite are exceeded we get, on the one hand, more highly silicified rocks, such as petrosilex and quartz-porphyry, and, on the other, with a deficiency of silica, we get the syenitic group of rocks.

The analyses in the following Table show the marked variability in

	Granite.				*Syenitic Granite.*	*Leptinite.*	*Granulite.*
	Noirétable, Lyons. (Mène)	Escherthal, Hartz. (Fuchs.)	Pargas, Finland. (Kuhlberg.)	Pargas, Finland. (Kuhlberg.)	Minnesota, U.S.A. (Streng.)	Pargas, Finland. (Fuchs)	Saxony. (Stebzner.)
	1.	2.	3.	4.	5.	6.	7.
Silica	70·0	75·46	65·85	75·15	67·70	72·70	75·80
Alumina ...	17·0	11·89	17·77	10·49	16·11	14·40	12·09
Iron peroxide	0·5	—	2·36	—	2·47	0·51	—
„ protoxide	—	3·52	1·54	1·13	2·29	—	2·18
Lime } ...	2·3	1·25	3·04	1·35	2·89	0·33	1·45
Magnesia }		0·08	1·57	0·71	1·11	0·12	0·38
Potash	7·6	4·40	2·57	5·08	4·47	5·79	4·27
Soda	1·1	2·56	3·26	3·34	3·64	3·47	2·72
Phosphoric acid	—	—	—	—	0·13	—	—
Water	0·8	1·12	0·76	0·80	0·83	0·86	0·63
	99·3	100·28	98·72	98·05	101·64	98·18	99·52

	Eurite.	*Gneiss.*			*Mica-schist.*		*Archæan schists.*
	Auvergne. (Lasaulx.)	Erzgebirge, Saxony. (Schéerer.)	Pargas, Finland. (Kuhlberg.)	Alps. (Schéerer.)	Saxony. (Fikenscher.)	Monte Rosa. (Zulkowsky.)	Urthonschiefer, Saxony. (Fikenscher.)
	8.	9.	10.	11.	12.	13.	14.
Silica	70·95	65·19	68·66	75·90	65·13	82·38	64·87
Alumina }	19·35	14·75	15·03	12·95	18·16	11·85	18·37
Iron peroxide }		6·88	1·92	1·31	—	—	—
,, protoxide	—	—	3·09	—	5·27	2·28	6·1
Lime	3·89	2·50	2·03	1·48	0·32	—	
Magnesia ...	—	2·04	1·97	0·16	2·70	1·00	2·22
Potash	3·23	4·77	2·47	5·12	2·99	0·83	3·01
Soda ...	0·92	1·99	0·64	2·39	0·53	3·80	0·62
Titanic acid .	—	0·87	—	—	—	—	1·63
Water	0·99	1·01	0·64	0·40	3·73	0·77	4·20
	99·33	100·00	96·45	99·71	98·83	99·49	101·05
+	CO^2 0·79				MnO 0·51	SbS 0·19	MnO 0·49

proportions in the chemical composition of granites: even Nos. 3 and 4, which are both from the same granite *massif* in the Isle of Pargas off the coast of Finland, show great variation in the proportion of silica. The granites of which the analyses are here given do not contain titanic acid;

but this substance is not at all of infrequent occurrence in granites [1]. The tables show also that, as a rule, the limits of variation of the commonly associated crystalline rocks are within those of the granite itself.

There are granites in which the proportion of silica is larger than in the above list, but there are few with less. The proportion of the other substances also varies considerably (*ante*, p. 41).

It is the Archæan rocks we must apparently look to as the chief source of the granites. Strata of Palæozoic age may however furnish the necessary materials and pass, by intense metamorphism, into granite. It may also often happen that the parent-rock of the granite is not the rock through which it rises at the surface, but a deeper-seated and unexposed rock. Mr. J. A. Phillips has shown, for example, by analysis that the bulk of the 'killas' surrounding the granitic bosses of Cornwall differs materially in its elements from the granite itself. At the same time there are more deeply seated beds which would lend themselves more readily to the necessary metamorphism, only there should be a difference in the resulting felspar. The parent-rock in this case may possibly be the older and probably underlying schistose and gneissic rocks, which crop out at the Eddystone and along the southern points of Devonshire. In the same way the granite of Wicklow is intrusive through Silurian strata, but older gneisses, which crop out at a distance of three miles from the granite massif, probably underlie the Palæozoic strata, and furnished the elements of the granite.

	Granite.		*Slate (Killas).*			*Carboniferous Sandstone.*	*Rhætic Clays.*
	Mitweider, Saxony. (Lemberg.)	Morvah, Cornwall. (Phillips.)	240 ft. deep, St. Austell. (Phillips.)	960 feet, Camborne. (Phillips.)	1290 feet, Dolcoath. (Phillips.)	Cumberland. (Phillips.)	Nièvre, France.
	1.	2.	3.	4.	5.	6.	7.
Silica	68·17	70·65	49·27	67·82	67·32	75·75	58·00
Alumina	16·34	16·16	18·00	9·56	20·85	8·23	20·00
Iron peroxide ...	2·32	1·53	12·68	tr.	2·83	10·52	4·00
,, protoxide ...	—	0·52	8·55	5·02	1·66	1·35	—
Lime	0·89	0·55	2·13	2·58	2·03	0·53	0·66
Magnesia	0·55	tr.	tr.	3·42	tr.	0·36	2·33
Potash	6·66	8·66	0·56	2·37	0·60	1·06	3·80
Soda	3·41	0·54	0·74	4·32	3·37	1·28	2·33
Manganese oxide	—	—	0·81	1·20	TiO 0·13	PO 0·15	—
Water	0·96	1·22	6·58	3·12	1·15	0·85	8·33
+	99·30	99·83	99·32	99·41 FeS 0·68	99·94	100·08 SO^4 0·17	99·45

Not only, however, do the older schists closely assimilate in composition to the granitic group of rocks, but there are newer rocks, such as Nos. 4 and 7 in the above table, rich in alkalies, which, under the action of metamorphism, might undergo analogous changes, or a change into the

[1] The oxide of Manganese is also of frequent occurrence in granites.

more basic syenitic group. The proportion of iron is a mere accident, and in a rock like No. 6 it might be readily replaced by alumina, or by a larger proportion of alkalies, at depths.

Accessory Minerals. The elements in the parent rocks, foreign to the constituent minerals of the granite, enter into other combinations with the surplus silica, and give rise to a variety of associated minerals. Amongst the most frequent of these are *tourmaline*, *garnets*, *iolite*, *zircon*, *gadolinite*, *allanite*, *andalusite*, *topaz*, *emerald*, and *pinite*. Besides these, *sphene*, *magnetite*, *titaniferous iron-ore*, *tantalite*, *molybdenite*, *fluor-spar*, *apatite*, and *cassiterite* also occur[1]. In gneiss, where the metamorphism has not been so extreme, the accessory minerals (p. 419) are less numerous.

Carbonate of lime is occasionally, though very rarely, a constituent of granite; and calcite, supposed to be part of the original rock matter, has been found crystallised in geodes. This is a point of considerable interest, as there is reason to suppose that originally the lime could only have existed combined in the silicates, and that the carbonic acid must have been subsequently derived from the atmosphere on the decay of these silicates; consequently the carbonate of lime in all probability found its way into the granite through the intermedium of derived or sedimentary strata.

Position and Age of Granites. We will now proceed to note the relation of granite to the surrounding rocks, and its relative geological age in this and other countries, and then give the reasons whether granite is to be considered as a rock of metamorphic or of igneous origin.

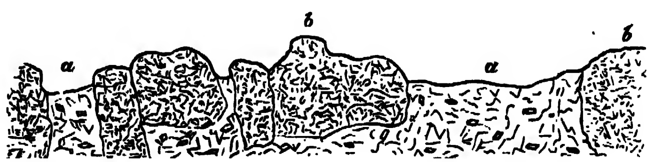

FIG. 212. *a. Porphyritic Granite. b. Schorlaceous Granite, Dartmoor.* (R. C. Godwin-Austen.)

England. In Cornwall and Devon the granite forms bosses of several square miles in extent, and rises at its culminating point at Dartmoor to the height of 2050 feet. It is generally light-coloured; and in some parts of Cornwall it contains large crystals of white felspar (porphyritic granite), and at other places numerous crystals of black tourmaline (schorlaceous granite). The granite has broken through and injected the surrounding Palæozoic rocks (Fig. 218, p. 444) up to the Carboniferous strata inclusive; and, as pebbles of the granite are found in the adjacent Triassic breccias, it is probably of Permian age[2]. According to Mr. Godwin-Austen there would seem to be two granites at Dartmoor,—

[1] Some of these, however, more especially the metals, may be of subsequent introduction.

[2] De la Beche's 'Geology of Cornwall and Devon,' p. 165.

an older one with schorl, *b*, broken through and enveloped in a newer and porphyritic granite, *a*.

The ornamental porphyritic granite of Shap, near Penrith, is of a dull-pink colour, with fine crystals of reddish felspar; and, like the adjacent Cumberland granites and syenites of Skiddaw and Eskdale, it may be of late Silurian or early Devonian age [1].

The hornblendic granite of Mount Sorrel in Leicestershire is intrusive through a metamorphic schist; but its exact age cannot be defined further than that it is of pre-Carboniferous date. The neighbouring syenites of Grooby and Markfield are shown, by Messrs. Hill and Bonney, to have been distinctly intrusive in Silurian slates, probably about the commencement of the Devonian period; while the greenstones of the Forest may belong to the period between the Coal-measures and the Keuper [2].

Scotland. The broad *massifs* of the grey granite of Aberdeen and of the red granite of Peterhead, together with many mountain masses in the Grampians, are surrounded by highly metamorphic and greatly disturbed strata of Lower-Silurian age; while the great bosses of the Southern uplands protrude also through Lower-Silurian strata, which are, however, less disturbed than in the Highlands and not metamorphosed except immediately round the granite. Dr. Archibald Geikie [3] notices a suggestive feature in the form of the latter, which presents more or less elliptical rounded or dome-shaped prominences, having a marked analogy with the stumps of some old volcanic rocks. These are Palæozoic granites, but he considers it almost certain that the granite of Arran (like that of Mull before described by Prof. Judd) is of Tertiary age.

Ireland. In Ireland the granitic range of the Dublin and Wicklow mountains forms the largest 'massif' of this rock in the British Islands, extending for a distance of 70 miles, with a width of from 7 to 17 miles, and rising through Lower-Silurian strata, which are metamorphosed by it. The intrusion took place certainly before the Carboniferous, and possibly before the Devonian period. The peculiar granite of the Mourne Mountains is probably of the same age. The gneissose granites of Donegal may be contemporaneous with the granites of the Grampians [4].

Jersey. In the absence of fossiliferous strata, the exact age of the granites and syenites of the Channel Islands cannot be determined. In all probability they are of a very early date, for a peculiar old conglomerate associated with the schistose rocks of Jersey is largely made up of granitic débris and pebbles [5].

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[1] Sedgwick's 'Geology of the Lake District;' and Ward, 'Quart. Journ. Geol. Soc.,' vol. xxxii.

[2] 'Quart. Journ. Geol. Soc.,' vol. xxxiv. p. 199, 1878.

[3] 'Trans. Edinb. Geol. Soc.,' vol. ii. p. 287, 1874.

[4] Jukes's 'Manual,' 3rd edition, p. 243; Hull's 'Physical Geology of Ireland,' 1878; Haughton in 'Quart. Journ. Geol. Soc.,' vols. xii, xiv, xviii, xx.

[5] Prof. Liveing in 'Proc. Camb. Phil. Soc.,' vol. iii. p. 75, 1877.

France. In France there are large tracts of granite in Brittany and Normandy. The ordinary fine-grained variety, which is closely associated with gneiss and mica-schists, is considered by M. de Lapparent to have been erupted after the Cambrian and before the Lower-Silurian period [1]. There is another Brittany granite,—often intrusive in the older variety,—generally porphyritic and associated with syenite and pegmatite, which is supposed to be newer than the Coal-measures.

The great granitic and gneissic plateau of Central France covers an area of not less than about 12,000 square miles. It consists of an older granite which is fine-grained, and associated with the great series of gneiss and mica-schists; and this also is succeeded by a porphyritic granite intrusive through the older rock. The first of these granites is older than the Coal-measures, which lie in places against the granitic flanks of the central plateau, and some beds of which consist largely of granitic débris and often contain granite blocks. The intrusive granite and quartz-porphyries are, on the other hand, newer than the Coal-measures [2].

In the Vosges, likewise, there are several varieties of granite. They constitute, amongst other masses, the central axis of the mountains, where they are associated with syenitic granites and granulites. The date of the eruptions of these masses would seem to extend from early Palæozoic times to the Permian period.

In the Morvan an older porphyritic granite is succeeded by an eruptive granulite which has broken through Devonian and Lower Carboniferous rocks, but does not seem to have disturbed the Coal-measures; a second disturbance took place between the Coal and Permian, but the more important one is that between the Permian and the Trias; while it was during the period of the Trias that the great system of quartz-sheets and -veins, before described (p. 338), was formed: another system of fractures and veins took place before the Pliocene period.

Pyrenees. In the Pyrenees there is a central axis of granite forming some of the highest peaks of that chain. The earliest eruptions were pre-Silurian, since pebbles of granite are found in some of the Silurian conglomerates; similar pebbles are also in the conglomerates of Permian and Triassic age [3]. Credner mentions a Pyrenean granite that contains a considerable number of rock fragments in which there are Jurassic fossils; and M. Leymerie was of opinion that in the 'Hautes Pyrenees' a granite is intrusive in slates of Cretaceous age.

Alps. In the same way in the Alps there are granites closely connected with the older gneisses and mica-schists, while there are others which are ascribed to Tertiary age; but it is a question whether in some

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[1] 'Bull. Soc. Géol. France,' 3rd series, vol. vi; Barrois, 'Ann. Soc. Géol. du Nord,' vol. viii.

[2] 'Explic. Carte Géol. de France,' vol. i. pp. 109, 192.

[3] De Lapparent, *op. cit.*, p. 1139.

cases these later granites have not been formed at earlier periods, and afterwards elevated *en masse* with the rest of the rocks. Many geologists have contended that the granite (protogine) of Mont Blanc and other districts must have been consolidated previously to their disruption and elevation, and that their subsequent protrusion is due only to that later disturbance which affected the whole of the rocks, including the underlying granite, composing the general *massif* of the mountain.

Scandinavia. The extended tract of schistose and granitic rocks that constitute, for a length of above 1000 miles, the Scandinavian peninsula, and stretches into Lapland and Finland, is of high antiquity. The granites are protrusive through Archæan gneisses, and near Christiania through Lower-Silurian schists; there is no evidence to show that any of these granites are of more recent date than the Silurian period. At St. Petersburg 650 feet of unaltered Silurian strata overlie a granite which had become cooled, consolidated, and partially disintegrated before the deposition of the Silurian beds.

Germany. The great gneissic and granitic tracts of Germany, such as those of the Erzgebirge, the Hartz, and Bohemia, are all referable to some part of the Palæozoic period. The granites are largely associated with syenites and are often intrusive.

Elba. The so-called granite of Elba, of early Tertiary age, is a rock considered by M. Michel-Levy to be in some respects more related to trachytes than to true granites [1].

America. While in Europe there is a doubt about the position or character of some of the granites referred to Jurassic or Cretaceous times, in Western North-America, where geological phenomena are on on so vast a scale, there are extensive tracts of, it is said, true Mesozoic granites. Zirkel divides the granites of the Fortieth Parallel into (1st) younger eruptive granite, probably of Jurassic age; (2nd) older eruptive granites of pre-Jurassic age (Palæozoic?); and (3rd) the granites which are inseparable members of the crystalline schists of Archæan age [2]. In the grand cañons of the Colorado River granite and gneissic rocks frequently form a platform on which rest horizontal strata of Carboniferous and Silurian age; while in the Sierra Nevada the grand massif of eruptive granite that constitutes the core of those mountains is considered by Professor Whitney to be of Jurassic age [3].

The granites of the Eastern States of North America are seemingly all associated with Laurentian and Huronian rocks, and therefore of Ar-

[1] 'Bull. Soc. Géol. France,' 3rd series, vol. iii. p. 227.

[2] Clarence King's 'Exploration of the Fortieth Parallel,' vol. i. chap. ii; vol. ii. p. 478, etc.; 'Microscopical Petrography,' chap. iii. 1876.

[3] M. Jules Marcou questions this conclusion, and is of opinion that the Sierra Nevada syenitic granite is of Palæozoic or Archæan age. 'Bull. Soc. Géol. France,' 3rd series, vol. xi. p. 429.

chæan age. It is the same in Canada, with the exception of the Eastern Provinces, where there is a fine white granite, intrusive in strata of Devonian age, and which underlies, without penetrating, Carboniferous strata[1].

In South America we again find the granite under two conditions: (1st) in association with gneisses and schistose rocks, forming continental areas in Brazil and adjacent parts of Eastern South-America, and probably of Archæan or early Palæozoic age; and (2nd) extrusive through rocks of more recent date, and forming axial masses of great dimensions, but of yet unsettled age, in the range of the Andes.

India[2]. The granites of the Indian peninsula, of which there are many masses and intrusive veins in the great gneissic tracts of the East and South-east, seem, with one exception, to be of Archæan age. Of this, which is in Lower Assam, it is difficult to make out the relations; it is certainly of origin subsequent to the great 'transition' series of India, while it can scarcely be of later than Secondary date. Granite is the axial rock of the main Himalayan range. The width of the band seldom exceeds 25 miles, and is generally much less. It forms the massive core of some of the highest peaks of those mountains, throwing out on their flanks a number of large dykes and veins. The granite is closely connected with the great gneissic series of this important mountain-range, and marks a line of eruption and disturbance of very early date.

Australia. It is the same in Australia, where a granite associated with gneisses and mica-schists forms an area almost continental in its dimensions in the south-western districts. It has a surrounding of Devonian strata, but its exact relation to these is not known. Other granites, apparently of Palæozoic age, form axial ranges in Victoria, New South Wales, and Queensland; they are eruptive through Silurian rocks.

There are large tracts of crystalline rocks and granites in Northern China; but of these little is known. The same remark applies to the eastern portion of Madagascar.

The Origin of Granite. The genesis of granite has long been the subject of fruitful controversy. Its crystalline structure, its evident initial plasticity, and its intrusion, in veins of the smallest dimensions, into the rocks in juxtaposition with it, led at first to the conclusion that it had originally been in a state of igneous fluidity; and this view is still held by some geologists, although generally with considerable modifications. The opinion, however, has been gaining ground of late years that it is to some extent, if not altogether, a metamorphic rock; but while some take the view that it is entirely metamorphic, others consider that there are granites of igneous, and some of metamorphic origin.

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1 Sterry Hunt, 'Survey of Canada for 1863,' pp. 430-434.

2 Medlicott and Blanford, 'The Geology of India,' vol. i. chaps. i. and ii, and vol. ii. p. 629.

It is contended by those who advocate the igneous origin of granite that its protrusion through the overlying strata,—its injection, as fine and thin veins, into the surrounding rocks,—the alteration or metamorphism of the strata in contact,—and the formation of dykes traversing adjacent strata, are points of resemblance in such close agreement with rocks undoubtedly igneous, that the origin of both must have been alike. But, as already shown, it was soon discovered that contact-metamorphism with granite never gives indication of the high temperature possessed by trappean and volcanic rocks, while the distance to which the metamorphism has extended may be a result of the greater mass of the granite or partly of normal-metamorphism.

Those who object[1] to the igneous origin of granite have pointed out that granite has not consolidated in the order of the infusibility of its constituent parts; but that its most infusible constituent (quartz) had solidified last. It has also been adduced that the specific gravity of the quartz of granite is 2·6, whereas that of silica, which had undergone igneous fusion, is only 2·2. David Forbes[2] showed, however, that these generalisations cannot be unreservedly accepted—that in modern lavas (Vesuvius) the refractory leucite has crystallised after the fusible augite—the former being sometimes superimposed on crystals of the latter. With respect to specific gravity, he remarks that the silica deposited from its gaseous compounds with fluorine, etc., and that organically formed in the frustrules of diatomaceæ, have a specific gravity of only 2·2, while quartz from lavas and trachytes is of the specific gravity of 2·6, and that, like the quartz of granite, it contains water-inclusions; also that other Vesuvian minerals, such as *idocrase*, *nepheline*, and others, all contain water. It is further observed that in certain distinctly igneous rocks, as for example some lavas, trachytes, etc., ordinary hexagonal crystals of quartz occur.

But neither does it follow that because the quartz of granite is like that of some undoubted igneous rocks, they both had a common igneous origin. There are particular forms of silica, such as one affecting a peculiar globular condition, and certain tabular crystals termed tridymite, the first of which occurs in some porphyries, and the second in a trachyte of the Drachenfels, which are never found in granite; whereas ordinary quartz-crystals occur not only in granite, but likewise in mineral lodes, in veins, and geodes, as separate crystals, as well as in unaltered sedimentary sandstones, in the gypsiferous beds of the Trias, and in chalk flints,—all of undoubted aqueous origin, and evidently formed under conditions of comparatively

[1] The reader should consult the original and exhaustive paper of Scheerer, 'Bull. Soc. Géol. France,' 2nd series, vol. iv. p. 468, 1847; Virlet-d'Aoust, *Ibid.*, 2nd series, vol. xv. p. 119, 1857; Daubrée, *Ibid.*, p. 93, and his other papers cited; Delesse, 'Bull. Soc. Géol. France,' 2nd series, vol. xv. p. 728, 1858, 'Le Métamorphisme des Roches,' 1869, and the other papers mentioned.

[2] David Forbes, 'Geol. Mag.,' vol. iv. Nos. 5 and 10, 1867.

ordinary temperatures and pressure. On the other hand, there is reason to suppose that the augite in lava may have been crystallised before the eruption of the lava, and the leucite subsequently to eruption; and that the ordinary crystals of quartz [1] in many volcanic rocks may have also been formed after eruption and during the cooling of the rock, or after the surface-waters had gained access to the lava. It is also very doubtful whether the *idocrase*, *garnet*, *mica*, etc. found in the ejected limestones of Somma were not formed before they were detached from the parent rock (*ante*, p. 208), at no very great depth, and not after enclosure in the lava during eruption.

Amongst the other reasons assigned why granite has not been in a state of igneous fusion is that it contains certain minerals which would have had their physical and optical properties altered by heat. Thus it has been found that the *allanite*, *gadolinite*, *pyrorthite*, and *orthite* possess a phosphorescence, which they lose when heated, and that *cymophane*, *brookite*, and some *felspars* have their optical properties altered by the same cause. M. A. Favre states also, speaking of the Alps, that the amethyst in the granite contains a volatile substance which is driven off by heat, and that the quartz often encloses very fusible minerals, such as *molybdate of lead*, *sulphide of antimony*, etc. Again, as bearing on this point, Elsner found that fused hornblende takes in cooling the form of augite.

Further, not only do the constituent minerals of granite, syenite, quartz-porphyry, and gneiss contain water, while lava, basalt, and obsidian contain none, but the accidental minerals found in granite also often contain water in still more considerable proportions. Tourmaline, allanite, talc, and hornblende have been found to contain 5 per cent., and iolite 1 to 3 per cent. of water. On the other hand, glassy inclusions, so characteristic of the really igneous rocks, are not found in granite and the associated group of rocks.

Independently of the jointing of granite, which often produces a very deceptive stratiform appearance, an apparent bedding, sometimes very marked, has often been noticed. M. Favre considers that the granite of Mont Blanc shows distinct stratification. In this country the Mount Sorrel granite certainly looks as though it had been bedded, and in the older granites of Brittany this quasi-stratified structure is often very distinct.

In one part of the Sierra Nevada the granite is stated to present many evidences of former stratification, among which are the characters shown in the following sketch (Fig. 213). These vertical masses of rock rise to the height of from 50 to 150 feet above the crests of the ridge,—

[1] This, however, would not apply to the small crystals of quartz found in the trachyte of Ponza, which are considered by Mr. Sorby to have been formed under a pressure of 4000 feet of rock.

a structure brought out more clearly by weathering. This, however, requires confirmation, as jointing might produce a similar appearance.

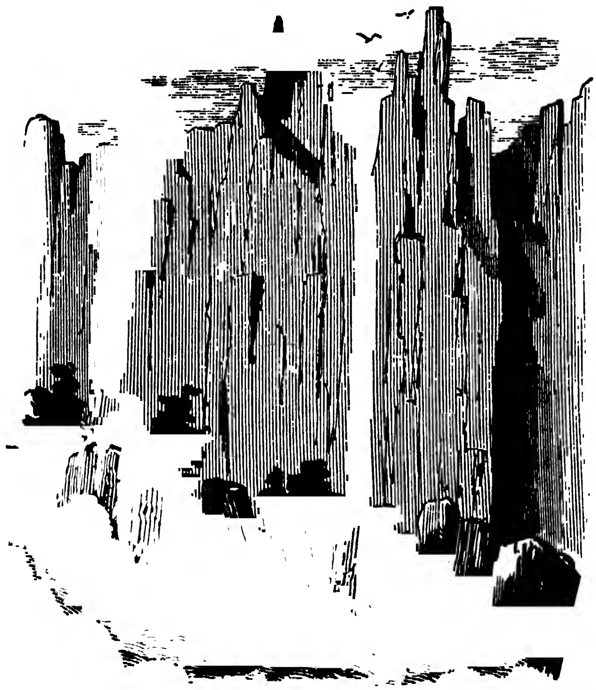

FIG. 213. *Sketch of Granite-masses near Canson, Nevada Territory.* (W. P. Blake.)

Liquid Inclusions. That water was present during the solidification of granite was proved by Sorby in his well-known paper[1] on the liquid and gaseous inclusions of the quartz and other minerals of granite, and has since been corroborated by the researches of Clifton Ward[2] and many other observers. These experiments show that during the solidifying of the quartz of granite water and various salts were present, traces of them now remaining included in the rock in innumerable microscopic cavities. In the quartz of some granites they are not more than $\frac{1}{1000}$th of an inch apart, and so minute that a thousand millions are said to be contained in a cubic inch. They make up as much as 5 per cent. of the volume of the rock, and the proportion of liquid is equivalent to about 1 per cent. of its bulk (Sorby, p. 34). Clifton Ward even speaks of the contained water sometimes making up at least 5 per cent. of the volume of the containing quartz. The fluid in the quartz cavities is, according to Sorby, *water* holding in solution the chlorides of potassium and sodium, the sulphates of

[1] 'Quart. Journ. Geol. Soc.,' vol. xiv. p. 453, 1858, and subsequent papers.

[2] 'Trans. Cumberland Assoc.,' part iii. p. 11, and 'Quart. Journ. Geol. Soc.,' vols. xxxi and xxxiii.

potash, soda, and lime, and sometimes probably free hydrochloric and sulphuric acids. The solutions are often supersaturated. In some cavities liquid carbonic-acid has been suspected. In others fluoride of calcium and water containing hydrofluoric acid have been noticed. Liquid cavities are rare in the felspar; only a few occur in the mica[1].

Rock-pressure. The cavity, which at first has been filled with the vapour, now contains a liquid-bubble, indicating a contraction of the vapour from a once higher temperature. On heating the specimens again to a certain point, the bubble disappears, and the vapour of the liquid refills the cavity. Taking size, heat, and compression as the data, Sorby, by means of an ingenious mathematical formula, calculated the depth and pressure under which the inclusions, to exhibit their present conditions, could have been originally formed, and came to the conclusion that the granites of Cornwall were, as a mean, consolidated at a temperature of 216° C., and under a pressure of 50,000 feet of rock; while the Highland granites, as a mean, indicate a temperature of 99° C., and a pressure of 76,000 feet of rock. The extreme temperature for the granite of St. Austell was 256° C. (493 F.), and minimum pressure 40,300 feet; on the other hand, the granite of Aberdeen indicates a temperature of 89° C. (192 F.), and pressure of 78,000 feet; while for an elvan at Gwennap in Cornwall, the estimated temperature was 320° C., and pressure 18,100 feet. Mr. Ward came to very similar results with respect to the granite and granitoid rocks of Westmoreland and Cumberland,—or that the *mean* pressure under which those rocks were consolidated was equivalent to that of 44,000 feet of rock.

Are we however warranted in supposing that there has been denudation to the extent of removing such enormous masses of rock as this would imply? Both Sorby and Ward felt this difficulty; and, in explanation, suggested that the feet-pressure they give may also represent the pressure (or tension) of elevation (*during* protrusion). Sorby, from the circumstance that the microscopical structure of the mineral constituents of granite is analogous to that of minerals formed at great depths and ejected from some modern volcanoes, considers that granite may have been formed under similar physical conditions, 'combining at once both igneous fusion, aqueous solution, and gaseous sublimation.' Not that the water at great depths dissolves the rock, but the water combines with the rock, in the way of rendering it more fusible; and he is therefore led to conclude that the pressure under which granite consolidated was analogous to that of lavas 'solidified at the foci of their activity, as though these rocks (granites) were the non-erupted lavas of ancient volcanoes variously protruded amongst the superincumbent strata.' But the argument is based to a great extent on the condition of

[1] See 'Micrologie Pétrographique,' p. 154.

the quartz in the trachyte of Ponza. There is however reason to suppose that trachytes may be not unfrequently formed by re-fusion of granite (Auvergne, Colorado); and, if so, the quartz might change in shape and size, but still retain the original liquid-inclusions, only modified in form. This would seem to be the case in this instance, where instead of the round and larger cavities of granite-quartz, the cavities of the Ponza trachyte are represented as small, elongated, and drawn out.

There are other elements in the problem which also raise a doubt as to whether the definite figures above-named can be accepted,—such as the minuteness of the objects, the variation in the size of the inclusions themselves in the same material, and especially the adopted rate of increase of temperature with depth, which is, I think, placed too low. On the latter grounds alone, the estimate would admit of considerable reduction. For example, instead of a temperature of 680° Fahr. (the solidifying point of some granites) lying at a depth of 53,500 feet, it should be placed, if we take the rate of increase of 1° F. for every 48 feet of depth, in place of the lesser rate adopted, at about 30,000 feet. It is also open to very great question whether at the time that the granites were consolidated, either the surface temperature or the rate of increase with depth were the same as at present. While, however, differing on the precise details, we have to agree in the main with Sorby's general inferences.

Atmospheric Pressure. There is also another possible source of pressure, that should, I think, be taken into account, with respect especially to the earlier formed granites, and that is, the greater extent and pressure of the atmosphere (*ante*, p. 416), which would have materially increased the boiling-point of water at the surface of the ground, and have affected the whole of the underground isotherms. The problem, therefore, is one of extreme complexity. I do not see that, in the existing state of our knowledge, the various elements admit of exact determination. All those we have mentioned, and possibly others, must be taken into consideration in a speculation of this character. All we can say at present is, I think, that granite must have consolidated under considerable pressure, and at a temperature probably not exceeding about 700° Fahr., or under that of low red heat; and it is not impossible that the change may have been effected under even a lesser temperature, but at what depth it is not possible to say.

Action of Water. Are we then to consider with some geologists that granite is an igneous rock, like lava, to which water has gained access, producing a sort of hydro-igneous fusion; or are we to adopt an opinion which has been gaining ground of late years, that granite is only an extreme phase of metamorphism, and has been formed by the re-fusion of the older sedimentary strata; or are we to suppose with others that there are granites of igneous and intrusive origin, and others of hydro-

thermal and metamorphic origin? All the elements of granite are certainly present in gneiss, mica-schist, and other schistose rocks, and approximately in the same proportion (*ante*, pp. 35, 422), just as we have in some of the shales and clays of ordinary sedimentary strata the chemical constituents of slaty and schistose rocks. In all these rocks water of imbibition is also generally present. Too much importance must not, however, be attached to chemical composition. The range in the proportions of the several elements is so great in granites (*ante*, p. 41), and also in gneisses and other crystalline rocks, that they may have been originally represented by shales and slates on the one hand, and by argillaceous sandstones on the other. The elements really essential in those cases, after silica and alumina, are the alkalies. Some clays, such, for example, as those which form certain beds of the Infra-lias of South-eastern France, are rich in alkalies, but usually they are, with some exceptions, either wanting, or are present in very small quantities in most sedimentary strata. The tegel (a clay) of the Vienna Basin, which is of Miocene age, contains however as much as 2·08 per cent. of potash and 3·16 of soda. Where the strata have been derived directly, in the manner described in Chapter IV, from the decomposition of igneous and plutonic rocks, we may expect to find, in addition to their insoluble matter, a variable proportion of their alkaline components retained in the strata thus formed.

While I have contended (*ante*, p. 212) against the probability of water reaching to deep-seated volcanic foci, where the heat cannot be under about 3000° F., it is quite possible to conceive it to penetrate to the lesser depths where the temperature would not exceed 600° or 700° Fahr.,—more especially at periods when the heat of the surface was greater, and the higher isotherms at less depth than at present, and when the folds of the earlier rocks formed long and continuous planes of dip at high angles, serving, as it were, as ducts for the surface-waters. These waters charged with carbonic acid would, in passing through such strata, have, with the depth, increased not only in temperature, but also in saturation, in consequence of the alkaline carbonates and soluble silicates set free by the decomposition of the constituent minerals of these strata. The experiments, before described, of Senarmont and Daubrée have shown that waters of this description, under the pressure they would acquire at depths, can act upon all the mineral constituents of granite. Professor Way also has shown that silica in the form of ordinary chalk-flint is soluble in alkaline solutions even at a temperature of 300° F.

Hydro-thermal Fusion. Under these circumstances, therefore, it is quite possible to have at a moderate temperature and depth all the conditions necessary for the hydro-thermal fusion of the gneisses and schists,—for the determination, by elective affinity, out of the viscid or plastic mass, of the constituent silicates of granite,—and for the liberation of the residual

quartz in the state of soluble or colloid silica. In this condition, the viscid silica solidifies with extreme slowness, and is also easily acted upon by acidulated waters; so that its solidification might follow long after the crystallisation of the felspars, micas, etc. In this way it seems possible to account for the order of consolidation of the constituent minerals of granite, —for the liquid inclusions,—and for the formation and injection of the intricate and minute granite-veins, and especially of the quartz-veins, into the fissures or cracks of the surrounding rocks; whether produced by rending or by contraction in cooling. Granite may thus be considered as the same rock but in a stage of metamorphism more advanced than gneiss and schists, and in which there was, therefore, greater freedom of motion amongst the constituent molecules,—in which, in fact, granite would have the more complete fluidity of a molten igneous rock and would act as such wherever it was placed under conditions such as would render it protrusive.

Another reason in favour of this view, rather than of deriving gneiss from granite, is, that if the latter had been the case, it is certain that during the decomposition and reconstruction of the granite, a large portion of the constituent alkalies would have been carried away, as is the case now in the formation of kaolin, whereas many of the gneisses and schists contain as large a proportion of alkalies as the granite itself, and this is what we might expect with the conversion of those rocks into granite, but not otherwise.

Further, the presence of granite as a constituent member of the Archæan series admits, on this view, of ready explanation. For, owing to the variable composition of the beds in the original series of these early sedimentary deposits, and to variations in the proportion of the water of imbibition, the different beds would be differently susceptible to the influence of metamorphic action. Some, therefore, would yield more readily than others to hydrothermal fusion,—whence those intercalations of granite so common in the various Archæan schists and gneisses.

CHAPTER XXIV.

METAMORPHIC AND PSEUDO-IGNEOUS ROCKS (*continued*).

CONTEMPORARY OPINIONS RESPECTING THE ORIGIN OF GRANITE. INCLUDED ROCK-FRAGMENTS. APPARENT DISCORDANT CONTACT WITH THE SCHISTOSE ROCKS. TRANSFERENCE OF THE UNDERGROUND ISOTHERMS. OTHER CAUSES AFFECTING UNDERGROUND TEMPERATURE. EFFECTS OF CLEAVAGE-PLANES AND FOLIATION ON CONDUCTIVITY. ORIGIN OF GRANITE BOSSES. AXIAL LINES OF GRANITE. QUARTZ PORPHYRIES, SYENITES, ETC. THE DEEP-SEATED BASIC IGNEOUS ROCKS. TIME AND ORDER OF SUCCESSION OF THE ACIDIC AND BASIC ROCKS. VOLCANIC ACTION OF PAST TIMES IN ITS RELATION TO THE PRESENT.

Contemporary Opinions. The belief in the metamorphic origin of granite has of late years been rapidly gaining ground amongst some of the most experienced field-geologists. So competent an authority as Sir Andrew Ramsay says of the old rocks of Anglesea, that it is impossible to work amongst them without being impressed with the idea that the granite and its veins 'are merely the result of a more thorough metamorphosis than was attained in the production of the associated gneiss; that is to say, that absolute fusion of portions of the strata occurred under such conditions of depth beneath the surface that a re-consolidation of those fused portions produced granite.' Patches of gneiss are in that district intimately associated everywhere with the mass of the granite, and the stratified rocks close up to its margin dip indifferently towards and from it 'as if part of the strata had been used up for the making of the granite itself.' The strike of the granite and of the strata is also the same[1].

The late Professor Beete Jukes also drew attention to the circumstance that one of the Leinster sections figured by Dr. Oldham showed a granitic ridge on the top of which are beds of mica-schist bedded horizontally with, as it were, veins of granite, while on the flank of the ridge the schists dip at a high angle towards the central mass, and terminate downwards against an irregular surface of granite. In other cases the granite comes bare to the surface of the ridge. This granite seems, as it were, to have eaten its way upwards through whatever lay above it. He considered that in such cases there could be little doubt of the granite being a metamorphic rock. The granites of Galway and Donegal are with difficulty separable from the surrounding gneiss[2].

The American geologists, who have worked in the boundless regions

[1] 'Memoirs Geol. Survey.' vol. iii. 2nd edition, p. 243, 1881.

[2] Juke's 'Student's Manual,' 3rd edit., 1872, pp. 146, 242, 366.

of the Western States, in describing the Middle-Park division of Colorado, state that the series of rocks, as a whole, is a great system of ancient sedimentary strata that have undergone the most perfect metamorphosis, the result of which over large areas has reached the last term of metamorphism, namely, structureless granite [1]. They consider the metamorphism to be of pre-Silurian age. The few remnants of structure that are yet visible in this mass conform to the surrounding system of folds of the Rocky Mountains.

With respect to the granites of Southern Colorado, they incline to the opinion that a very large portion of them are metamorphosed Silurian, Devonian, and, in rare instances, even Carboniferous strata. In the Quartzite Mountains especially, they observed the direct transition from sedimentary beds into typical granite. They consider the trachytic rocks and some of the rhyolites to be highly fused granites. The latter overlie the granite, and enclose fragments of it in a semi-fused state [2].

Professor Clarence King, in describing the results of his extended observations along the 40th parallel, expresses the opinion that the great masses of crystalline schists and allied granites of that region were all formed out of pre-existing sediments; but he considers that, for the genesis of granite, tangential pressure, such as that exhibited in the elevation of mountain-chains, is necessary;—this pressure having the effect of breaking up the horizontal arrangement of the crystallising schists and crowding them into the structureless mass of granite [3].

Dr. Sterry Hunt concludes that in many cases the Canadian and East-American granites have been introduced into the surrounding rocks in a fused state; but, at the same time, he considers that it is equally likely, and in many cases more probable, that the granite is only the result of an extreme stage of metamorphism, and that the process which at certain stages only gave rise to gneiss, when carried a step further went to the length of fusing the rocks it affected [4].

Other geologists might be quoted for similar opinions, but it will be better now to give some of the facts and arguments that have been adduced in support of these views.

Included Rock-fragments. If granite be a rock thus derived from others by extreme metamorphic action, we should expect to find traces and fragments of the original rocks imbedded in its mass. Nor is evidence of this description wanting. Inclusions in granite are common; but the student must be careful to distinguish not only between concretions, but also between the fragments of rock caught up from strata,—in no way

[1] Prof. Hayden's 'Report' for 1872, pp. 138–143.
[2] *Ibid.*, 1876, p. 105, and 1875, p. 214.
[3] *Op. cit.*, p. 112, 1878.
[4] 'Survey of Canada for 1863,' p. 267.

related in their elements to the granite,—through which the granite is intrusive in bosses, dykes, or veins, and those inclusions which may be remnants of the original parent-rock left in the granitic mass. In this respect, granites which are of Archæan age present a marked distinction from those of later date.

Dr. James Geikie, in a paper on the metamorphic origin of granite, states that in the grey granite of the southern uplands of Scotland he finds 'nests' of altered rock, consisting of dark fine-grained or semi-crystalline rock, often showing traces of lamination. Sometimes there is a sharp line between the granite and the included fragments, at other times the passage is gradual. They may be remnants of thin bands or beds of shale interleaved in the original strata, from which the granite has been derived by metamorphic action; for, if they were fragments broken off, they should be more abundant near the junction, which they are not. Dr. J. Geikie concludes that these granites have resulted from the alteration *in situ* of certain bedded deposits [1].

Mr. J. Arthur Phillips, in a paper 'On Concretionary Patches in Granite,' in which he considers the distinction between inclusions and concretions, expresses the opinion, that the schistose inclusions in ordinary eruptive granites can only be regarded as fragments of extraneous rocks caught up in the granite; but that in granites of metamorphic origin they may be looked upon, by those entertaining that opinion, as portions of the older rocks which have withstood the metamorphism. Mr. Attwood considered that these inclusions were most common near the junction of the granite with the surrounding rocks, but Mr. Phillips thinks not [2].

The late David Forbes stated, that his wide experience in the field, assisted by the microscope and laboratory, satisfied him that very many of the so-called granites and gneisses are really sedimentary products of the breaking up of true igneous eruptive rocks, stratified by aqueous agency, and subsequently, as it were, reconstructed or consolidated. At the same time, he had come to the conclusion that there are also true eruptive granites of igneous origin, i.e. the products of action similar to volcanoes [3]. Metamorphic changes might, he believed, have taken place whilst the rocks were in a solid condition by what might be termed moleculo-chemical action.

Included fragments of rock are common in the granite of Central France. Dufrénoy mentions that the fine-grained granite forming the axis of the Forez Mountains frequently contains isolated blocks of gneiss, although this rock does not exist in the chain itself. Fragments of gneiss

[1] 'Geol. Mag.,' vol. iii. p. 529, 1866.
[2] 'Quart. Journ. Geol. Soc.,' vol. xxxvi. p. 1, 1880.
[3] 'Journ. Chem. Soc.' for June, 1868; and the 'Geol. Mag.' for Oct. 1867

are of frequent occurrence in the granite near Brest. The porphyritic fundamental granite of the Vosges is in some places full of fragments of gneiss, the angles of which are blunted, while the granite wraps round them as a pasty body modelling itself upon them[1]. In the same way, the granite of Annonay, in the Ardèche, is loaded with fragments of gneiss.

In the Pyrenees, at the Maladetta, segments of gneiss of very large volume are imbedded in the granite. In another part of the Pyrenees (Neouvielle) the granite contains fragments of mica-schist; while in the granite of Cherbourg are found fragments of syenitic-gneiss. In most instances the imbedded fragments have retained in a remarkable manner their original schistose or stratiform structure.

The granite of Table Mountain, Cape of Good Hope, contains fragments of slate, but these possibly may be caught up and not the original rock.

Inclusions are common likewise in the American granites; and mention is made of a granite in Colorado that encloses masses of schistose rock *several hundred feet* in extent, which pass by imperceptible degrees into the surrounding granite;—'they are not broken off and enclosed portions of schists, but remnants of bedding not obliterated by metamorphism.'

Probably one of the finest exhibitions of the internal structure of granite is that afforded by the magnificent precipice of El Capitan in the Yosemite Valley, which presents a smooth vertical wall 3200 feet in height. Upon its face, which is in general of a uniform gray colour, are seen irregular cloud-like masses and rudely lenticular bodies, some consisting of black hornblende and quartz, and others of black mica and orthoclase. Professor Clarence King considers that these inclusions are mechanical, not chemical, accidents; and that they may be regarded as enveloped bodies, which, for some reason or other, have resisted the tendency to become merged in the main body of granite[2].

Fig. 214.—*Section of Stievesmaddy Hill, Mourne Mountains.* (Reduced from Irish Geol. Survey.)
s. Silurian strata. *b.* Basaltic dykes. *gr.* Granite. *g.* Glaciated surface with large granite boulders.

Discordant Contact with the Schistose Rocks. Some physica phenomena seem inexplicable upon any other hypothesis than that of the change by metamorphism of the schistose rocks into granite. For example, in the Mourne Mountains, the granite rises to a height of nearly

[1] 'Explication de la Carte Géologique de la France,' vol. i. pp. 130, 194, 328.
[2] 'Exploration of the 40th Parallel,' vol. i. pp. 115, 118, 120.

2000 feet, and is overlain at places by Silurian schists much crumpled and dipping downwards, as it were, into the granite. These schists are cut through by dykes of basalt, none of which however enter the granite, both the schists and basalt ending abruptly against that rock, as shown in Fig. 214, as though a more extreme metamorphism had transformed a portion of the deeper seated beds into the plutonic rock. The case mentioned by Ramsay, and just referred to, seems analogous.

It is of peculiar interest to find that the same phenomenon had not escaped the notice of so accurate an observer as MacCulloch at a time when the belief in the igneous origin of granite was universal, and the structure represented could only be looked upon as an unaccountable anomaly. The following is a reduction of the section that he gives of an instance of this kind in the Western Highlands,—but of which he offers no explanation.

FIG. 215. *Junction of Granite with Stratified Rocks, west coast of Scotland.* (MacCulloch.)
gr. Granite. *p.* Schistose rocks.

Transference of the Underground Isotherms. From what we have previously said (p. 413) it will easily be understood that, if certain stratified rocks were carried by subsidence to such depths, and were so covered up by newer strata as to become subjected to a temperature due to central heat, of from 600° to 700° Fahr., metamorphism of intensity sufficient to produce the conversion of these strata, first into schistose rocks and then, if the action were sufficiently strong and prolonged, into granites, might ensue; always provided, of course, that the original stratified beds contained the necessary chemical elements and a certain quantity of water. The strata subject to such alteration would also only be those that contained the amount of alkalies indispensable to the change, and these would be most abundant in those strata which were derived directly from the decomposition of the earlier igneous and crystalline rocks. As the superficial area occupied by strata of this character would diminish in proportion to the spread of the sedimentary strata, the formation of the granitoid rocks is, as a rule, in relation to the antiquity of the strata, being most frequent in the Archæan rocks, less in the Palæozoic rocks, and further decreasing in the newer strata, where both the requisite thickness of cover and the other necessary conditions became rarer and scarcer.

Sir J. Herschel and Mr. Babbage long since made it evident that if strata

be accumulated in a deep sea, or in an area of continued depression, the bounding surface of the earth's internal temperature will immediately begin to migrate upwards, and the isothermal planes will be displaced throughout the entire depth of the overlying rocks[1]. Thus, the former bottom of the ocean at that place, 'will after a long period, and when a fresh state of equilibrium is attained, acquire a temperature corresponding to its then actual depth, while a point as deep below it as itself is below the surface will have acquired a much higher temperature, and may become actually melted, and this without any transfer of matter in a liquid state from below.'

Other Causes affecting Underground Temperature. Unless, however, there is some disturbing cause, the isothermal planes will remain parallel to the bounding surfaces, which we may assume to be nearly horizontal. To what then are we to attribute (in the absence of fracture and disturbance) such a deflection of the thermal planes as would enable the plastic mass below to work its way towards the surface? Two causes may be assigned. It has been ascertained by experiment, that even pure water will act on felspathic rocks and take up a portion of their alkalies; if the water holds carbonic acid in solution, it will take up more than double the quantity; and if pressure and heat be added, the quantity dissolved is very largely increased. Consequently, the surface-waters in passing downwards, especially through crystalline and Archæan strata, will carry with them a certain quantity of potash and soda, and that quantity will increase in proportion to the depth and to the amount of decomposable alkaline silicates present in the rocks,—as for example, more in gneissic rocks than in mica-schists. Further, where lateral pressure had effected a crumpling and folding of the strata,—so general at that early period,—the water would pass more readily downwards in those areas than in others where the beds retained greater horizontality. In such cases, therefore, the conductivity and the fusibility of the rocks would alike be increased both by the presence of more water and of waters more alkaline.

Effect of Cleavage-planes and Foliation on Conductivity. With the crumpling and folding of the strata, other causes affecting temperature come into operation. These causes are those which are dependent upon the conductivity of rocks as influenced by physical conditions, and not by their chemical composition. Amongst these are cleavage and foliation. Messrs. Herschel and Lebour found for example that, apart from the differences caused by differences of lithological composition and moisture, the conductivity of rocks was materially affected by

[1] 'Quart. Journ. Geol. Soc.,' vol. ii. p. 596, and iii. p. 186.

the position of the cleavage planes. Thus, slates give the following result[1]:—

	Absolute thermal Conductivity.	Absolute thermal Resistance.
Slates, taken across the planes of cleavage . .	00·395	253
" " along the planes	00·561	184

M. Jannettaz[2] has also shown that the conductivity of rocks for heat is influenced in a remarkable degree by the planes of cleavage of

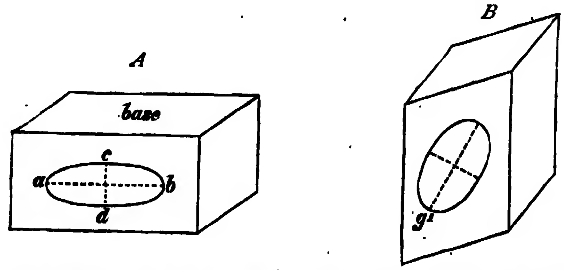

FIG. 216.—*Diagram showing the greater Conductivity of certain Crystals along the Planes of Cleavage.* (Jannettaz.)

In Mica (Fig. *A*) heat passes along the line of main cleavage, which is parallel to the base of the crystal, with a rapidity represented by the line *a*, *b*; whilst at right angles the rate of conductivity is represented by *c*, *d*; the curve connecting these lines *a*, *c*, *b*, *d* is called the thermic curve.

In Pyroxene, var. diopside (Fig. *B*), the direction of these lines of conductivity is similarly shown in the dotted lines and curve g^1.

the component minerals of the rock; and that with micaceous rocks especially this property manifests itself to an exceptional extent. He ascertained by experiment that heat was transmitted along the planes of cleavage parallel to the base of crystals of mica with a rapidity two-and-a-half times greater than perpendicularly to that plane, as represented in Fig. 216, *A*.

The difference is also considerable in the pyroxenes, and varies in the different species. *B* represents the thermic curve of diopside. It is the same with the hornblendes, but in a different degree.

We have here precisely the mineral predominant in gneisses and mica-schists; and accordingly M. Jannettaz found that heat was transmitted much more readily along the planes of foliation in such rocks than in a direction perpendicular to them. When the rock is homogeneous or crystalline, but structureless, as in granite, the thermic curves form a sphere; but in schistose rocks they form ellipses, the axes of which, taking the one in the plane of foliation and the other perpendicularly to it, give the measure of conductivity in the two directions. The relation of the minor axes, taken as unity, to the major axes gives the excess of con-

[1] Report, British Association for 1881, p. 130.

[2] 'Bull. Soc. Géol. France,' 3rd series, vol. ii. p. 264; and vol. iii. p. 499.

ductivity in the one direction over the other. These are found in the following rocks to be as under:—

In Argillaceous Schist (average)	1·000 :	1·250
In the Slates of Angers (Lower Silurian)	„	1·600
„ „ Deville (Cambrian)	„	1·988
In the Mica-schist of Aurillac (Archæan)	„	1·820
In the Gneiss of St. Gothard (Archæan)	„	1·500
„ „ Calasca (Archæan)	„	1·630

The relative lengths of the thermic axes vary with the schistosity. In some of the more granitoid gneisses, the major axis is to unity as little as 1·06; while in some mica-schists it exceeds 2; and in a talc-schist it reached 2·007.

Origin of Granite Bosses. Consequently, where the dip of the strata has been greater than elsewhere, or the foliation more developed, or micaceous rocks more predominated, there the conductivity has been greatest and the transmission of the central heat most rapid; whence it is possible that there may have resulted in different areas great variations in

FIG. 217.—*Theoretical Diagram illustrating the possible origin of some Granitic Bosses.*
p. Palæozoic Strata. *a.* Archæan Schists. *gr.* Granite. *i.* Isothermal line of depth,—horizontal from side to side before the folding of the rocks at *x*, but as the folding took place, rising at *m* in the curve here represented.

the metamorphic action at equal depths. Further, in areas where these conditions were favourably combined, and where in consequence the isothermal lines rose above the normal level, the temperature of the strata traversed by the higher isotherms might become sufficiently high to produce hydro-thermal fusion. In such a case, we might have the mass of rock so affected progressively eating its way upwards by the gradual ascent of the isotherm of fusion, until the crust at that point, rendered thinner either from this cause, or by denudation proceeding on the surface above, yielded to the pressure (however caused) of the underlying molten rock.

Thus, let *a* in Fig. 217 represent the Archæan, *p* the Palæozoic rocks (or any other suitable rocks), and *i* the level of the underground isothermal line of—say 650° Fahr. before the disturbance which crushed the rocks at *x*. If, then, by the folding and crumpling of the crust at *x*, and the consequent production in that area of a vertical cleavage and vertical dip of the foliation, the conductivity of that part of it is increased, the line *i* will rise at *m* nearer the surface, and as it rises will produce hydro-thermal softening or fusion, and reduce by this more extreme metamorphism the rocks it

traverses to the molten structureless state of granite. As this fusion proceeds the superincumbent load becomes lessened, and the force, whatever it be, which drives upwards the plastic granite *gr*, will tend to uplift or to break through the remaining weakened cover, and either form an underground boss or ridge of granite to be exposed by subsequent denudation, or else will cause fracture of the strata, and the protrusion of the granite through, or with, the disrupted rocks.

In this way the granite may retain its original connection with the Archæan schists, as in the granitic plateau of Central France; or it may

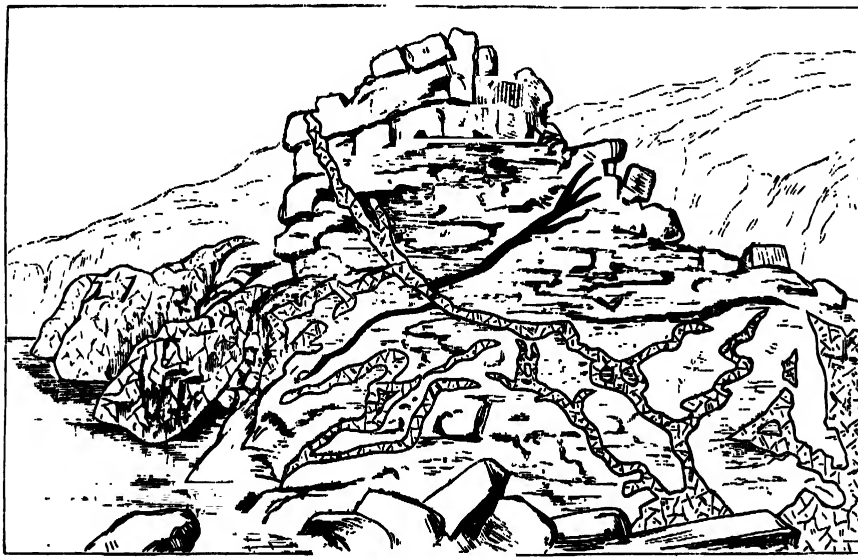

FIG 218. *Granite- and Quartz-Veins in Killas, Polmeer Porth, Cornwall.* (Reduced from a sketch by Dr. Whewell.)

have forced its way beyond them, as in the case of the granite bosses of Cornwall and Devon. The relation of such bosses to the surrounding strata has, on the supposition of their being intrusive in the same sense as when we speak of ordinary igneous rocks, been difficult of explanation, inasmuch as they are not on any line of fracture, and the lines of strike of the strata are continued in the same direction on either side of the protrusive granite, as though there had been an uplifting *en masse* of the overlying strata, and, as it were, *replacement* without the usual *displacement* of the strata accompanying the intrusion of true igneous rocks. The broken schist *in situ*, which in parts of Sardinia, according to Fournet, overlies the granite, and increases in quantity with the ascent of the plateau, may be the result of the fracture of this outer crust by some such uplifting [1].

[1] General De la Marmora's 'Voyage en Sardaigne,' vol. i. p. 440, 1857.

As the fused viscous or plastic granite became intrusive, and rose, in Cornwall and Devon, in dome-shaped masses or bosses, portions of it were at the same time injected into the many fissures and cracks of the overlying rocks, caused by their emergence (Fig. 218).

There are also cases where the granite was solidified underground without protrusion, in which areas the granite will have remained as the fundamental rock, and be only visible where it has been exposed by subsequent denudation; but, in cases like those above mentioned, it is clearly protrusive and intrusive.

In the preceding observations I have here considered the folding and crushing of the rocks at x apart from the question of Regional Metamorphism, which would further affect the general temperature of the mass and the position of the isotherms.

Axial lines of Granite. While this mode of eruption may have given rise to bosses of various magnitudes, or even to quasi-continental masses, another cause may have determined its appearance along lines of great disturbance. In those colossal folds and anticlinals which have accompanied the elevation of mountain-chains, such as the Alps, the Pyrenees, the Vosges, etc., a granitic core is commonly exhibited along the line of the main axis, or parallel to it, although not always continuous, nor always of dominant importance. A previous partial emergence of the granite here may have assisted in producing a line of weakness; but, as a mass, the granite is generally, in these cases, only to be looked upon as participating in the general upheaval, due to lateral pressure, and is not to be considered intrusive in the ordinary sense of the word.

For the granite in these centres would seem frequently to have been solidified before fracture took place, so that it merely participated with the superincumbent rocks in the general movement, and came in the main, if not entirely, solid to the surface. This is the conclusion formed with respect to the Alps by so competent an authority as M. Alphonse Favre. The grand granite buttresses of Mont Blanc stand out not less boldly and sharply than do the gneissic and schistose peaks of the adjacent mountains; and, although they rise steep and abrupt, there appears to have been no yielding of the base, as there would in all probability have been had the mass been plastic; and much less is there any appearance of flow, such as would have resulted from a more liquid state of the granite[1]. Still the granite might throw out veins from the deeper-seated and more highly heated portions.

This subject is one so full of interest that I regret the limits of this work prevent me from pursuing it further. The hypothesis of the meta-

[1] 'Recherches géologiques sur les parties de la Savoie, etc., voisines du Mont Blanc,' vol. iii. p. 141, 1867.

morphic origin of granite, according to which all our massive and solid granites are derived from certain sedimentary and schistose strata, by the combined action of heat, pressure, and moisture,—and are the result of a chemical and mineralogical transformation, due to a phase of extreme metamorphism,—is both conformable, on the whole, with the general conditions of the problem, and also meets certain physical difficulties which no other hypothesis so satisfactorily accounts for.

Quartz-porphyry, etc. If such be the origin of granite, it almost necessarily follows that a group of associated rocks, such as granulite, quartz-porphyries, elvanite, pegmatite, and some felsites (eurite), should be placed in the same category. These rocks are commonly found in close relation with granite; they have a similar chemical composition, and the differences may be due either to rate of cooling, or to the effect of more complete fusion. It is owing certainly to a more rapid rate of cooling that the outer portions of a granitic boss sometimes have the fine granular texture of a felsite instead of the crystalline structure of a granite; on the other hand, in the case of the quartz-porphyries, the original fusion may have been more complete.

The group of syenitic rocks, including the syenitic granites and the more felspathic binary syenite, which physically have the same bearing and appear under the same conditions as granite, are only terms of a series of which granite is the type or centre.

It is easy to imagine that, if the amount of sedimentation were greater than shown in Fig. 217, the strata *a* might be depressed beyond the line (*i*) of the melting-point of granite, or to a depth at which fusion would be more perfect. It is possible that such a temperature would be reached at a depth of 40,000 to 50,000 feet,—a thickness attained in many places by the Archæan and Palæozoic rocks. It must also be remembered, as before mentioned, that in the earlier geological periods the rate of increase of temperature with depth was, in all probability (owing to the causes before named), more rapid than at the present day.

In this way the porphyries and quartz-porphyries which have broken through the granites may represent the product of the greater changes induced by a more complete fusion; while the products of a still more intense heat and more igneous fusion, and of more rapid cooling, would be the vitreous and glassy acidic rocks of this group, or of their altered existing representatives.

The deep-seated Basic Igneous Rocks. At yet more profound depths lie, in all probability, the denser basic rocks which have risen to the surface in a state of complete igneous fusion, but of whose genesis otherwise we know nothing. We cannot, as with granitic rocks, trace them back step by step through parent-rocks of sedimentary origin; nor are we able to connect them with any other pre-existent surface-rocks. We know they have broken through, not only all the sedimentary strata, but

also through the granites and other rocks of metamorphic origin, whence we infer that they underlie these. We have reason to believe also that the surface-waters never reached the magma in which they originate, and that it was not until they broke from their abyssal recesses that in their ascent they came within the influence of water-formed strata and surface agencies; but on this point there are great differences of opinion[1]. Direct evidence is necessarily unattainable in face of the inaccessible depths at which these complex phenomena take place, and the impossibility of penetrating through more than a mere fraction of the intervening rocks. Still, little as is known, that little gives us certain temperature- and chemical-data, which, combined with the ascertained structure of such portions of the deep-seated magmas as extrude on the surface, enable us to infer, with more or less certainty, the hidden conditions under which these rocks were formed.

Time and Order of Succession. Before concluding this chapter, there are two other questions with respect to the volcanic and plutonic rocks that should be mentioned, as they have both given rise to much discussion. One of these is, whether or not there has been any definite order in the manner or the times at which the two classes of rocks have risen to the surface, or whether, with respect to these, the basic or the acidic varieties predominated, one more than the other, during past or recent geological periods; the other question is whether volcanic action is as rife and powerful now as during the past periods of the earth's history.

With respect to the first of these—one party maintains that there has been a definite sequence from the granites, porphyries, felstones, and other acidic rocks of the earlier geological periods, to the dolerites, basalts, and lavas of more recent times; the other, on the contrary, contends that there has been uniformity throughout, both in the character of the eruptions and of the rocks—that trachytes, andesites, obsidians, etc. of the more recent geological periods represent, as fully as the granitic rocks did in earlier times, the acidic group, and that granite is only of rarer occurrence at the later periods of geological history, because, being a rock formed at great depths, it is by long denudation alone that it is exposed at the surface. Time thus being a factor in the case, the granites of the age of the Palæozoic series, which have suffered the longest denudation, are more opened out to the surface than those of the age of the Secondary and Tertiary strata where denudation has told less. This might be true if it be assumed that all granites had consolidated under a cover of from 30,000 to 50,000 feet of superincumbent rocks, but this, as we have before shown, there is reason to doubt.

[1] See Dr. Sterry Hunt's 'Chemical and Geological Essays,' chaps. i. and vi.

It is also to be observed that the granite of Mount Sorrel was already exposed in Triassic times, that of Dartmoor probably in Permian times, that of Central France in Silurian times, and the granitoid rock of St. David's at the commencement of the Cambrian period; while the large continental areas of Scandinavia, Eastern North-America, Eastern South-America, South-eastern India, and many other smaller tracts, were raised to the surface in Archæan or Palæozoic times, and have since continued to form part of the continental land-surfaces. On the other hand, instances are not wanting, though they are few, of granites of Mesozoic and Tertiary age; and there is nothing to indicate in these instances that it is owing to unusual or exceptional conditions that the granite shows on the surface. If, also, time brings a gradual increase to the total mass of the sedimentary strata, on the other hand, the thickness of the Archæan and Palæozoic strata is so greatly in excess of that of the Secondary and Tertiary series, that a much less denudation of the latter than of the former would suffice to produce exposure. Again, in judging of the age of granitic eruptions, it does not follow that, because a granite is brought to the surface by the flexure of the crust in the formation of a mountain axis, it is to be considered as appertaining to the age of that axis. It may have been, as before mentioned, a substratum of granite formed at a long anterior period. If, however, a portion of it retains sufficient viscidity to become intrusive, it may then, as a matter of classification, be considered to be a contemporaneous granite.

Secondly, it is true that dolerite, melaphyre, and other basic rocks like those of the present day, are met with in strata of Palæozoic and even Cambrian and pre-Cambrian age, and that trachytes, rhyolites, and other acidic rocks are common in Tertiary and recent times; but the former bear a very small proportion to the granites, porphyries, and felsites of the earlier geological periods; and the latter form masses which, though actually large, are insignificant in comparison with the enormous outpourings of basaltic and doleritic rocks of later times. Some geologists also consider that the character of those newer acidic rocks presents more essential points of difference in mineral composition from those of the earlier periods than appears to exist in the basic rocks.

Volcanic Action in Past Times. With regard to the character of the volcanic action in early geological times, the case is not quite so clear. The levelling effects of time have been urged in explanation of the rare occurrence of old volcanic cones, and the many so-called volcanic necks have been adduced as proof of the existence on those spots of active volcanoes. Many of these necks may, however, be merely intrusive rocks, finding their way to the surface at points of least resistance, as with the great Whin Sills of Durham and Northumberland. There is,

in general, a want of connection of these isolated bosses with quâquâversal (periclinal) lava-flows, and other accompaniments of an ordinary subaërial volcano. Ashes, it is true, might have been easily removed, yet the great so-called ash-beds of Cumberland and Wales, which are thousands of feet thick, still remain, although they are referred, by those who rely on denudation, to explosive action. It must also be remembered that the sections of old volcanoes, where such do exist (Figs. 199 and 200), show that it is possible for volcanic cones to survive the destructive effects of time, even in a highly glaciated, and excessively denuded, land.

Much more likely also would be the preservation of volcanic mountains, composed, like that of Mauna Loa, of lava-streams only; and yet with very few exceptions, and those on a scale far smaller than the great volcanic mountains of Iceland, Hawaii, and other volcanic centres, none of this character have been met with. There is nothing we know of in the Palæozoic or Mesozoic series comparable in magnitude, even as represented by a worn-down base, with these newer volcanic mountains.

The old igneous eruptions have evidently been in great part fissure-eruptions; and it is probable that many of the ash-beds may be, not the result of subaërial explosions, but of weathering and disintegration or of the breaking-up and comminution of lava- or trappean-streams in presence of water. Fissure-eruption does not exclude explosive action; but there is nothing to show that this action was on the same scale of magnitude and permanence as those of late Tertiary and recent date. With the greater inertness of the earth's crust, and the greater resistance presented by its rigidity, volcanic eruptions must, with time, as suggested long ago by Elie de Beaumont, have altered with the alterations of these conditions and may now be exhibited under a phase very different from those of the earlier periods.

The eruption of igneous matter generally was most frequent and continuous in Cambrian and Palæozoic times, and became less frequent in Secondary and Tertiary times. On the other hand, although the intervals were longer, the enormous fissure-outwellings—amongst others, those of Jurassic or Cretaceous age in India, and of Miocene and Pliocene age in North America and Europe—are unequalled in horizontal extension at any earlier period of the earth's history; while on the contrary there is no evidence in early geological times of such masses of accumulated lava-flows from a central crater as those named above, or even such as those of Teneriffe and Etna, or of explosive outbreaks like those of Coseguina and Krakatoa at the present day. This is due indirectly to the same cause—that is, secular refrigeration. The crust of the earth, at first thinner and more flexible, yielded more readily to the disturbing influences caused by its contraction.

With the lapse of time and the loss of heat, the thickness and the rigidity of the crust increased, and consequently the frequent changes

dependent upon its greater mobility during its earlier stages occur at longer intervals in later geological periods, while they are unknown in our limited experience. The explosive catastrophes of modern times are not the consequences of any remarkable dynamical disturbances of the crust, for the changes of level are unimportant, and the discharge of lava is not necessarily excessive; but they are due to the accidental circumstance of the eruption taking place near the sea, and to an unusual influx of water into the crater. So far from these being great eruptions in the sense of a rapid and excessive extrusion of molten matter (this would rather tend to the exclusion of water), they are mainly the consequence of a slow though steady rise of lava, which, as explosion succeeds explosion, is blown out and followed by the influx of large bodies of water, which are successively flashed into steam.

These are questions which must be to a certain extent theoretical, and about which great differences of opinion are inevitable, owing to our ignorance of so many of the conditions of the problem, and to the obscurity attendant upon extreme distance in time. But with increasing light and the setting in of conditions gradually assimilating to those of the present day, we have data respecting both these and other geological phenomena more comparable with those of the present times. The gradual building-up of the sedimentary strata and the introduction of life furnish us with a roll-call which is daily being rendered more and more complete, and which, although there are breaks in the record, can be interpreted with very considerable certainty and precision; and this evidence it will be our object to lay before the student in the second and concluding part of this work.

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END OF VOL. I.